![EVONIK Leading Beyond Chemistry]

ELEMENTS

Research. Knowledge. The future.

1/2020

Industrial Production

From the steam engine to 3D printing

Industrial production A production method characterized by a highly developed division of labor, a high level of capital investment, and larger production volumes than those of manual methods. After emerging in England in the 18th century, industrial production spread throughout Europe in the course of the 19th century, spurred by innovations such as the steam engine. The next major breakthrough came in 1931, when Henry Ford launched assembly-line production, thus paving the way for standardized mass production. The way companies produce their products is still being continuously refined today. In the latest phase of this evolution, additive manufacturing methods are making it possible to produce complex and customized components.

Henry Ford (1863–1947) Founder of the Ford Motor Company
Mass production The manufacture of large numbers of identical products consisting of standardized individual components
Additive manufacturing A computer-controlled production process in which a material is deposited layer by layer to build a three-dimensional object.

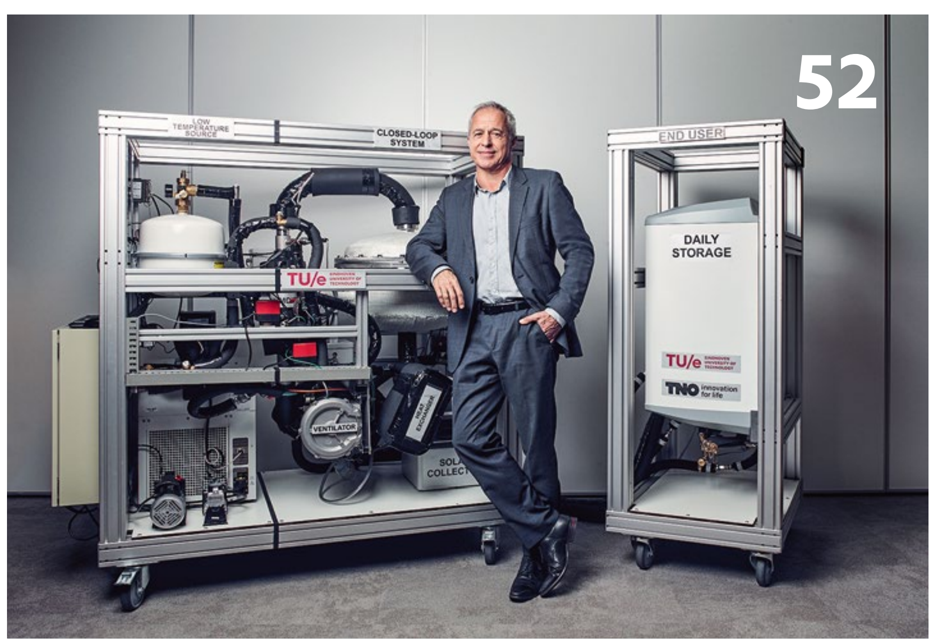
→ More about 3D printing starting on page 10

DEAR READERS,

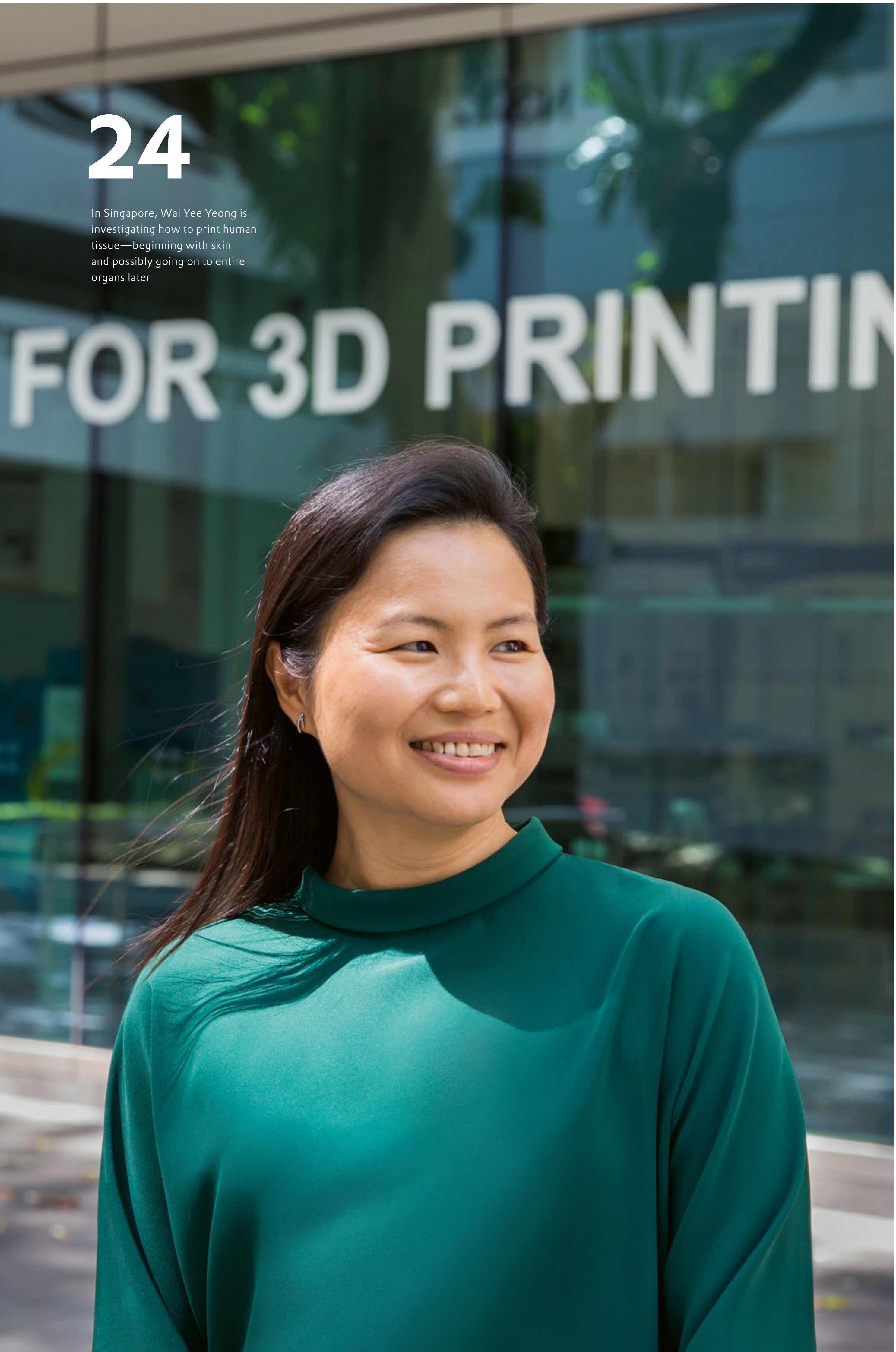
The intrepid boy reporter Tintin was one of the great comic-book heroes of my childhood. Together with his dog Snowy, Tintin became world-famous. But the real hero of this wonderful comic-book series was someone else: the brilliant and slightly hard-of-hearing Professor Calculus.
He was the first man in the world to build a submarine with a shark design and to create the rocket that successfully landed Tintin and Snowy on the moon. And a full 50 years ago, he invented a technology that is finally becoming a reality today: a 3D photocopying machine. Three cheers for Professor Calculus!
The threshold we are now crossing is the one that leads to series production. To date, 3D printers have mainly produced prototypes and single items. The cost and time involved were only secondary considerations. But in the mass production of components, things will be very different. In the future, these components will have to compete with traditionally manufactured products in terms of cost as well as production speed and quality. Exactly how and where this breakthrough will succeed is still an open question today. However, it's already certain that 3D printing has time on its side. And thanks to its innovations, Evonik is in the forefront of this development.
Whether renewable energies will one day really be able to fill the world's needs affordably and reliably depends crucially on how we can store electrical and heat energy in the future. More than 200 years ago, the Italian physicist Alessandro Volta invented the first battery, which was able to store electrical energy for long periods of time. The battery developers of today are engaged in an exciting competition. Rechargeable batteries need to become ever more lightweight, more safe, and simultaneously more powerful. That applies not only to lead-acid and lithium-ion batteries. These criteria are even more important for the solid-state batteries of the next generation, which are currently being developed in laboratories. In this issue we take a bold look into the future.

I wish you a thought-provoking reading experience!

Matthias Ruch
Editor in Chief



The Dutch researcher Olaf Adan with a prototype of the heat battery



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In Singapore, Wai Yee Yeong is investigating how to print human tissue—beginning with skin and possibly going on to entire organs later

DECEPTIVELY REALISTIC

The biotech material from Modern Meadow looks like leather—but it isn't. The New Jersey-based US startup creates this vegan product from collagen produced by means of a fermentation process that uses yeast cells. In the future, the finished material could replace leather made of animal hides in products such as shoes and handbags. In the fall of 2019 Evonik's venture capital unit bought shares in Modern Meadow—thus helping to shape a future in which people can do without leather.

A LOOK AROUND THE WORLD

Innovations from science and research

Emissions catchers on wheels

Swiss researchers are aiming to reduce the climate impact of trucks—with a CO_2 storage unit on the roof

According to the European Environment Agency (EEA), trucks were responsible for about a fourth of the CO_2 emissions in road traffic in 2017. That's a considerable challenge for climate protection. But now researchers at the Swiss Federal Institute of Technology Lausanne (ETHL) have developed a concept that aims to drastically reduce truck emissions. The CO_2 is collected in the tailpipe of the truck and then cooled and liquefied—in a two-meter-long collection capsule on the roof of the vehicle. A key role in this process is played by oxygen and nitrogen, which help to separate the carbon dioxide from other gases. The collected CO_2 can be pumped off at special service stations and subsequently processed into synthetic fuels, for example. The ETHL researchers Shivom Sharma and François Maréchal aim to reduce total truck emissions by as much as 90 percent. The two scientists are now planning to develop a prototype.

PEOPLE & VISION

"Our findings could make ice removal child's play in the future"

THE MAN

Joseph S. Francisco, 64, grew up in Beaumont, Texas, near huge factories and petroleum refineries that discharged pollutants into the air. Early on in his career, he started to focus his research on the connection between air pollution and respiratory illnesses. That was the starting point for a decades-long career as an atmospheric chemist. Francisco has taught and conducted research at numerous universities in the USA, Europe, and Asia. Today he is a professor at the renowned University of Pennsylvania, where he is investigating previously unexamined chemical reactions in the Earth's atmosphere.

THE VISION

The team of scientists led by Francisco is studying the growth of ice. The team recently achieved a breakthrough: By using a visualization they were able to show what happens at the level of atomic structure when ice is formed in the atmosphere. This sounds abstract, but it could soon have practical consequences for the use of wind energy in the winter. That's because when wind turbines ice up, they often break down. The findings of the US researchers could help to make the de-icing process much faster and more economical—and thus give wind power an additional boost.

Bending, not breaking

Flexible airplane wings make flying more environmentally friendly

The aviation sector is a pioneer in the field of lightweight construction. In order to reduce kerosene consumption, aircraft manufacturers have for years been using materials that are lightweight yet stable, such as plastics reinforced with glass fiber or carbon fiber. The Institute of Aeroelasticity at the German Aerospace Center (DLR) is collaborating with Delft University of Technology to further decrease the weight of airplane wings. The researchers have built an aeroelastic airplane wing that is longer, lighter, and more elastic than conventional wings. Thanks to specially aligned carbon fibers, the wings can twist under high pressure so that strong gusts of wind do not generate any additional lift.

SOLAR TRANSITION

Researchers at Nanyang Technological University (NTU) in Singapore have developed a recycling method in which plastic waste is converted into valuable chemicals with the help of sunlight. The heavy metal vanadium acts as a chemical catalyst that promotes the disintegration of molecules of plastic under the influence of solar radiation. The result of this process is formic acid, which can be used, among other things, to generate electricity in fuel cells.

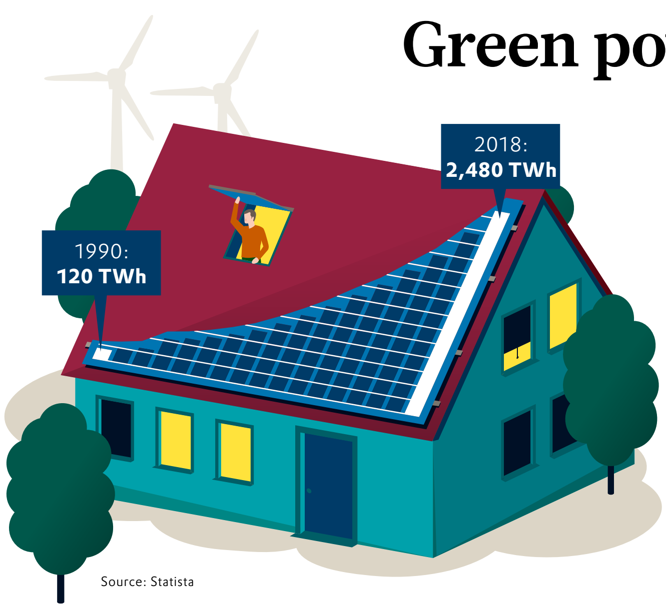
25

PERCENT

of the greenhouse gases that are currently emitted every year can be saved by 2050 through the use of innovative chemical technologies, according to a study of the International Council of Chemical Associations (ICCA). The biggest potential is offered by solar cells, amino acids for animal nutrition, and battery storage systems.

THAT'S BETTER

Green power



In spite of all the obstacles and difficulties, the energy transition is a success story. Global consumption of renewable energy from the sun, wind, and water has been growing steadily at high rates of speed. In the past three decades, it has increased by a factor of more than 20. China is the front runner, outdoing the United States and Germany by a significant distance.

Worldwide consumption of renewable energies in terawatt hours (TWh)

GOOD QUESTION

"Professor Hu, will we soon be able to use wood to cool our homes?"

Yes, but not regular wood. By removing lignin from conventional wood and pressing it, my team and I have created a bleached "white wood," which has two benefits. On the one hand, it hardly heats up at all when it's exposed to the sun. On the other, it can radiate infrared energy into its surroundings. That's how the building is cooled down. The cooling effect is based on vibrations and the stretching of the cellulose molecules. As a result, the building does not require any additional cooling such as an air conditioning system. As we found out in our experiments, the building's energy consumption could thus be reduced by 20 to 60 percent. The material's long-term durability—up to 20 or 30 years outdoors—remains to be evaluated. But we are optimistic that for some special cooling applications, such as roofs in a dry environment, the wood could be used within a few years.

Liangbing Hu is a professor at the University of Maryland. Together with his team, he is working on new, innovative uses for wood.

THERE'S MORE STILL TO COME

TEXT **GEORG DAHM**

The automotive industry is considered a pioneer in 3D printing. BMW, for example, turns plastic into guide rails for car windows

3D printing is evolving from a niche process into a manufacturing technique for mass production. Evonik supplies customized materials for all the key technologies and is helping to promote the development of the next generation of printers

It's clear that object 3D-0426 was a failure. The result was a fuzzy grayish-white structure with ragged edges. It's hard to tell what it was originally meant to be. However, its neighbor, 3D-0308, is a splendid specimen. It's a clean and smooth sphere that seems to be itching to be used on the billiard table. Bags bearing cryptic lettering and filled with small, delicate sculptures, blocks, and spheres take up an entire shelf of the Evonik lab in the Marl Chemical Park.

Next to it are the cabinet-size 3D printers that made all of these parts from powdered material in cartridges. The objects are the result of test runs in which the appropriate printing parameters are sounded out, new formulations are tried out, and the properties of a batch of material are checked. This is accomplished by repeatedly printing the same standardized objects, which are then subject to standardized stress tests. Without such laborious quality checks, no company would be willing to have its products made by means of additive manufacturing, which is the technical term for 3D printing.

This nondescript lab is, to a great extent, helping to shape the future of additive manufacturing. "We ask companies what they are working on and what materials they will need five years from now," says Sylvia Monsheimer, who is responsible for the New 3D Printing Technologies Market Segment at Evonik. "By providing the right materials, we enable new printing technologies to be launched on the market."

ONE TECHNOLOGY—MANY POSSIBILITIES

Monsheimer travels a lot in her capacity as an ambassador for 3D printing. She has an outstanding network that encompasses technicians and engineers as well as the board members of well-known companies. She wants to make people more aware of how additive manufacturing might completely transform business models. For example, what would happen if a company could easily and quickly try out new manufacturing ideas on its own? If it no longer had to take the limits of a mold into account when designing components? Or if it could rapidly produce small batches that would be too expensive to make by other means? Monsheimer tells us about a visit she made to a textile factory that would like to switch its machines to new fabrics and patterns more quickly. "That's possible if you use printed parts," she says.

Although Monsheimer has been working on 3D printing for more than 20 years, she has never seen as much creativity and enthusiasm as in the past three years, she says. "For a long time, a few dominant →

At the Evonik lab in Marl, Sylvia Monsheimer is examining how the printing of a sample is getting along

companies hogged the market. Many of the basic patents expired between 2010 and 2017. Since then, many enhanced versions of these technologies have been introduced on the market. It's stimulating the entire sector." Evonik cooperates with many of these innovators. The Group's latest investments and partnerships in Israel, China, the USA, and Austria all serve to make additive manufacturing ready for mass production.

3D printing is steadily spreading throughout industry. One example is the automotive sector, where startups such as the US company Local Motors have made a name for themselves. The startup's autonomous electric shuttlebus "Olli" consists of 80 percent printed parts. These parts are produced by printers the size of garages. However, they basically work like the printers you can get for a couple of hundred euros at electronics stores. The printer heats a plastic filament from a roll and deposits it layer by layer. This technique is referred to as Fused Deposition Modeling (FDM). It's a robust method that doesn't produce any dust during the printing process. Moreover, professional devices produce such a precise result that they can print medical implants or copies of organs that surgeons can use to plan complicated operations.

One of the methods that BMW uses for additive manufacturing is Multi Jet Fusion

Evonik's Venture Capital unit recently invested in one of the technology leaders in this field. The company in question is the Chinese startup Meditool, which is working on the PEEK material from Evonik. This material is approved for medical use and Meditool uses it to create a variety of products ranging from cranial implants to artificial intervertebral discs (see the overview on page 14). Such partnerships provide the material developers at Evonik with insights into the idea pipelines of sector pioneers. In its discussions with these companies about new manufacturing techniques, Evonik finds out what properties future printing materials will need.

3D printers are now an established presence in the factory halls of automakers. Among them are FDM plotters from the Dutch startup Ultimaker. Its first DIY device caused a big stir in 2011 and helped fuel the hype around 3D printing. Today the company primarily targets professional users; VW, for example, uses Ultimaker printers to develop and produce tools and assembly aids at its factory in Portugal. As a result, the development costs have decreased by 91 percent, while the time savings even amount to 95 percent.

3D PRINTING FOR THE MASSES

However, FDM machines can’t produce components in large batches. The process is too slow even in high-performance printers, which create the parts by moving back and forth in a raster. “Additive manufacturing using powder is the only process suitable for producing large piece numbers in the foreseeable future,” says Thomas Grosse-Puppendahl, who is responsible for Evonik’s worldwide business involving 3D printing. These printers lay down polymer powders layer by layer and heat the material at the relevant points in order to fuse it together. This is mostly done using a laser, but new techniques promise to speed up the process. These printers generally use polymer powders from Evonik.

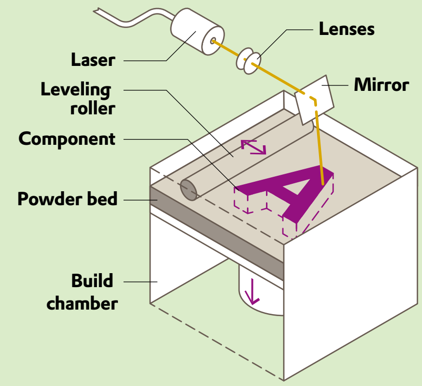
Examples include the gray machines from HP, which can also be found in the Marl technical center, where they carry out test runs next to the specimen shelf. The printer’s manufacturer, HP, which is well known in offices and homes, has transferred its expertise with inkjet printers to additive manufacturing. The component’s cross-section is printed onto a layer of polymer powder in black ink, and the heat lamps are then switched on. The black markings heat up faster than the other areas, so the material fuses together there; then the next layer of powder is laid down. The cycle of inkjet printing followed by heating is repeated again and again until a black and gray component is removed from the powder bed and blown clean under an extractor hood.

This technology is called Multi Jet Fusion (MJF). BMW, for example, is already using it in production. In 2010 BMW began to use plastic and metal-based processes, initially for small batches. According to the automaker, it has since then used additive manufacturing to produce more than one million components, including waveguide brackets for the Rolls-Royce Dawn and window guiderails for the i8 Roadster. The Group also uses 3D printing to produce customized decorative inserts for the dashboard and the body of the Mini.

3D printing is still being primarily used to create trim or small parts that are invisible to car buyers. This is not surprising, since every new application first has to prove its worth in less critical areas. 3D printing primarily has to compete against the well-established injection molding technique, which has been enhanced over a period of many years. The advantages of 3D printing are that it enables freedom in design and opens up completely new opportunities

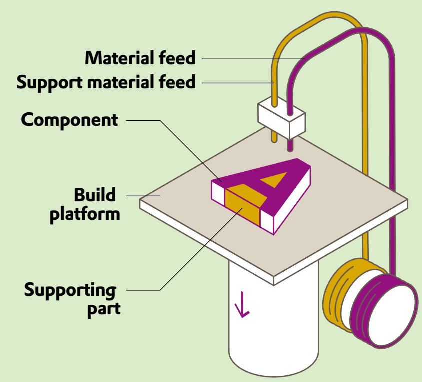
More on page 16 →

The Main Processes



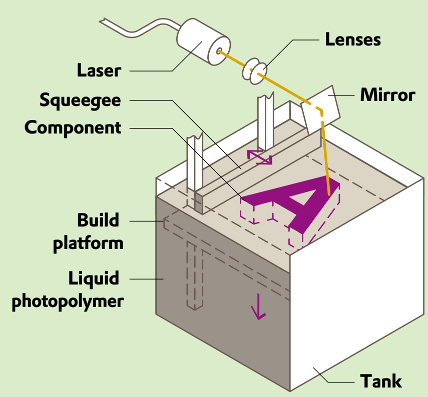
Powder Bed Fusion (PBF)

A powder is deposited layer by layer and fused at the places where a component is to be created. Depending on the method in question, this is either done by a laser (SLS) or an infrared light (Multi Jet Fusion/MJF, High Speed Sintering/HSS). In the second variant, an inkjet printer prints a black marking on the places that are to be fused. The black areas heat up faster than the unmarked areas. The finished component is then taken from the powder bed.



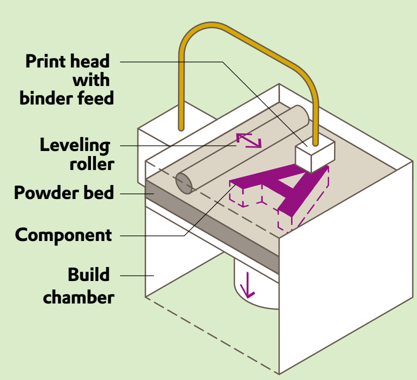
Fused Deposition Modeling (FDM)

The material in this process is a plastic filament that is supplied by a roll. A print head liquefies the material in a manner similar to a hot-melt glue gun. As a result, components are created layer by layer out of liquid plastic. A second print head adds support material, which it deposits into cavities and at overhangs, for example, because the component has to be reinforced in these areas during the printing process. This support material is removed after the component is finished.



Stereolithography (SLA)

The construction platform is submerged step by step into a tank full of light-sensitive liquid plastic (photopolymer). n each step, mirrors are used to guide a laser beam to the points where it hardens the plastic. The finished component is lifted out of the tank. Depending on the printing method used, the component then has to be hardened further and the support structures, which are printed along with the part, are removed.

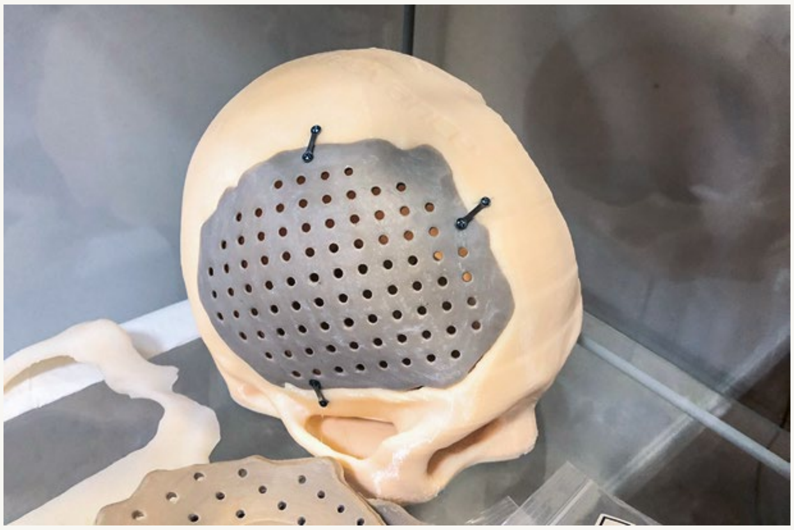


Binder Jetting (BJ)

Similar to the Powder Bed Fusion process, Binder Jetting uses a powder that is deposited layer by layer. However, the powder is not fused but instead is bound together with a binder that is applied by a print head. Binder Jetting is suitable for producing models for metal casting, for example, because they can be easily removed from the finished molds by burning out.

A Futuristic Quartet

New technologies require new partnership models. Evonik is cooperating with other companies worldwide in order to investigate promising future applications for 3D printing. Here are four examples



It's all in your head: Vestakeep® filaments are already used to make cranial, facial, and mandibular implants

MEDITOOL

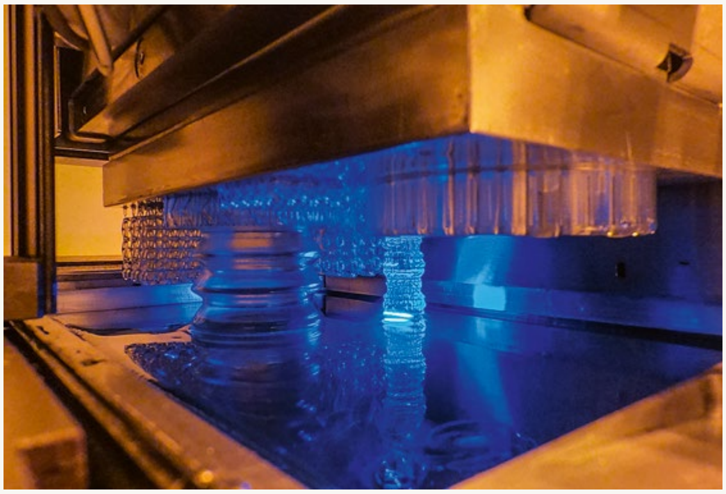
Artificial Bones

Artificial cranial implants, joints, and bone sections: "Nowhere else are the possibilities of 3D printing coming into their own as much as in medical technology," says Marc Knebel, who manages the medical business at Evonik's High Performance Polymers Business Line. "A customized product is created for each and every patient." In 2019 Evonik became the lead investor in one of the sector's most promising startups: the Chinese 3D printing specialist Meditool. The company, which is based in Shanghai, prints cranial, facial, and mandibular implants out of PEEK. This is a high-performance polymer that Evonik sells under the brand name VESTAKEEP®. Evonik was the first manufacturer to launch this plastic on the market as a medical-grade product. Meditool's long-term goal is to grow in an even more ambitious segment: implants for spinal disc surgery. One of the first products it has developed for this purpose are cages—artificial intervertebral discs with which body tissue grows together. Evonik and Meditool now want to jointly determine how the research and practical clinical work in this area are developing. "Meditool offers a unique combination of technical competence and clinical expertise," says Knebel. "We can help this company expand its global footprint."

CUBICURE

A Tough Material

Just one year after Cubicure was founded, the company held its first talks with Creavis, the innovation unit of Evonik, in 2016. Although the young company, which is a spinoff of TU Wien—formally Vienna University of Technology—has extensive experience with promising 3D printing methods, this field still presents it with numerous challenges. Stereolithography (SLA) creates components out of a liquid resin that reacts with light. The process is extremely precise, "but conventional resins are brittle and most of the finished parts have a lot of warping," says CEO Robert Gmeiner. The problem is that SLA techniques use low-viscosity materials. "It would be better to use high-viscosity resins and pastes, but they are still hard to work with," says Gmeiner. However, the Hot Lithography method developed by Cubicure enables such viscous materials to be processed with the help of a special temperature control system. In order to improve the technology further, Cubicure is cooperating with companies that to date have used injection molding processes. CAT scans show how close the new technology's results are now to those of the conventional manufacturing process. Evonik and Cubicure have together tested various raw materials. They have found a number of promising candidates among reactive polyesters. "We have since then worked together in order to pave the way for product development," says Gmeiner.



Cubicure's specialty is Hot Lithography, which processes special resins

To mold or to print? Castor helps companies decide which production process is the most economical

CASTOR

By Other Means

Castor supports manufacturers that are introducing 3D printing. This Israeli startup has developed a system that analyzes engineering designs using their underlying CAD files and simultaneously evaluates thousands of components. It works out what kind of geometry characteristics each component needs to have, what kinds of processes and materials could be used to print them, and whether 3D printing would pay off. Castor is initially focusing on complex components that are manufactured in small batches. Its customers include several Fortune 500 companies. "We help companies harvest very low-hanging fruit," says the company's cofounder and CEO, Omer Blaier. "We also help them to adapt their engineering designs to the 3D printing process." For example, the Castor system suggests which of the components that are located close together can be printed in 3D as a continuous workpiece. It also recommends service providers that support customers as they convert their production processes to 3D printing. Castor does not create any fundamentally new designs. "That's still the job of the engineers. We only help them along the way," Blaier says. He regards Evonik's entry as a new investor in Castor as a win-win situation: "Evonik receives access to additive manufacturing end users and to the problems they want to solve—and we're helped by Evonik's expertise as we improve our software."

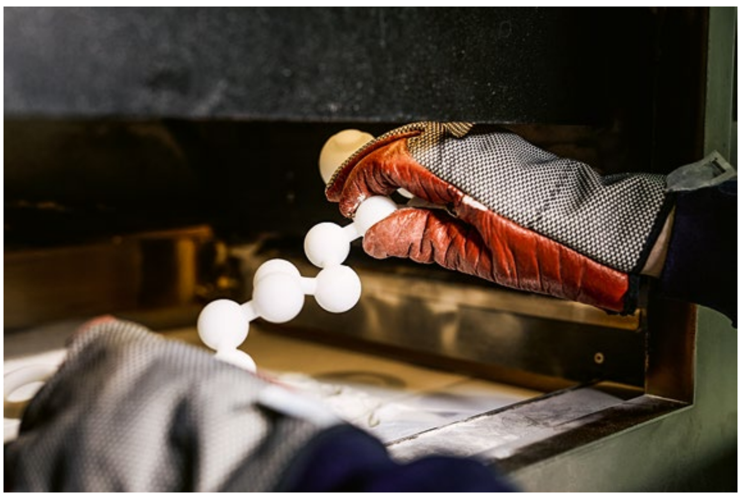
EVOLVE

Hot off the Press

It all began with a used digital printer that had been bought discreetly in an auction on eBay and then rebuilt in a garage. The US startup Evolve emerged from a development project of the 3D printing company Stratasys. Today Evolve's investors include Lego, and Stanley Black & Decker. The company's technology is based on laser printing. An image is created on a roller by means of an electric charge. Toner sticks to the charged areas, and the image is then transferred onto a high-speed electrostatic belt and transported to a layer bonding mechanism. "We first deposit the image layer by layer," explains the Vice President of Evolve, Rich Allen. "After that, we compress the structure while applying heat in order to produce a stable part." The main advantages of this process, which is now in the commercialization phase, are as follows: It's quick, because a complete layer of material can be deposited in one go instead of point by point. It prints a large variety of engineering-grade materials, because both the laser printing and the layer bonding process can handle a wide variety of materials. It can also print multi-materials within the same layer because it has five individual printing units. "In addition, because the particles are very tiny the image's resolution is extremely high compared to traditional manufacturing techniques," says Allen. Evonik has been working on materials for this process together with Evolve since 2019. "We became partners very quickly," Allen says. "Both Evonik and our company are aware of this technology's enormous potential for mass production."

Jetting along: Evolve's technology enables combinations of various materials to be printed quickly

VW plans to use 3D printing to produce customized parts such as gear knobs



In Marl, Evonik creates hundreds of test objects each week in order to improve materials and processes

for researchers and engineers to develop lightweight components and create totally new functions. “We are completely redesigning the parts for 3D printing so that they will have the properties we want,” says Monsheimer.

This process is simplified by a new partner of Evonik: the Israeli startup Castor (see the overview on page 15). The company’s software conducts a comprehensive technical and economic analysis in order to determine when additive manufacturing is economical compared to conventional production methods.

A component that is reinvented for 3D printing often has little in common with the original part. Whereas an injection-molded part has to be heavy and massive so that it can withstand great stresses, an equivalent 3D-printed part can have a seemingly filigree design consisting of arches, struts, and honeycomb structures. It can withstand stresses just as well as the injection-molded part but weighs only a fraction as much. As a result, even as simple a part as the window guide-rails of a roadster give us a preview of how entire automobiles will be built in the future.

LIGHTWEIGHT PARTS FOR FLYING OBJECTS

These weight reductions make additive manufacturing a very interesting technique for aircraft construction. Every gram counts in this sector, and there is a rising demand for more fuel-efficient machines that are less damaging to the climate. The innovations of additive manufacturing are initially inconspicuous here as well. The US Air Force, for example, uses 3D printing to produce replacement parts for its veteran jet planes. The fact that 3D printing made a toilet seat much lighter but still robust thanks to the use of a honeycomb structure was considered newsworthy within the sector. The components that are being developed by the aircraft manufacturers Boeing and Airbus are more critical to an airplane’s operation. Metal powders are now being used to make the first wing and engine components, and the 3D printing of plastic parts is becoming increasingly common for cabin furnishings. In this case, it would often also be too expensive to create injection-molded parts—for example, when an airline modernizes its fleet. Such tasks require the expertise of specialists like the Belgian company Materialise, which, among other things, uses high-performance polymers to print components for Airbus.

According to Monsheimer, greater production volumes will, more than anything else, require additive manufacturing to become faster. “The process will become especially interesting for the automotive industry when we begin to produce tens of thousands or hundreds of thousands of units,” she says. The new partnership between Evonik and the US startup Evolve (see the overview on page 15) might be the key to unlocking this potential. The startup’s technique, which is known as STEP, basically works like a laser printer and thus achieves much higher speeds.

“Conventional powder-based processes always us a laser or print head that traces the print shape on the powder bed,” explains Innovation Manager Wolfgang Diekmann, who heads the 3D printing lab in Marl. “STEP, on the other hand, uses digital printing technology. The material is very quickly picked up by a drum, which then deposits it. Because the powder is very fine, the resulting component has a higher resolution than would otherwise be the case.”

> “We have to completely redesign parts for 3D printing”

THOMAS GROSSE-PUPPENDAHL,
HEAD OF THE ADDITIVE MANUFACTURING INNOVATION GROWTH FIELD AT EVONIK

Evonik is contributing its decades-long experience with materials to the partnership, creating a win-win situation in the process, says Monsheimer. “We can develop new materials when we have a machine that we can test them with. Our partners, in turn, can develop a new machine when they have access to good materials,” she adds. As a result, the technical center in Marl is a veritable exhibition of the international 3D printing sector. In addition to machines from HP and 3D Systems, the center has devices from the German market leaders EOS and Voxeljet, the Swiss company Sintratec, and the Chinese manufacturer TPM. The devices are extensively used, as is demonstrated by an opened printer that Monsheimer is inspecting. “We want to know not only which materials we can develop for existing technologies but also how the existing technologies might be made better,” she says.

ADDITIVES FOR NEW PROPERTIES

This approach has enabled Evonik to more or less incidentally develop several 3D printing technologies of its own, which it licenses to other companies. “We have experimented with variants of High Speed Sintering (HSS),” says Monsheimer. In this technique, the powder is not directly melted by a laser, but instead an absorber is applied at the desired points. A heat source is then passed across the layer, similar to the approach used in Multi Jet Fusion.

Obtaining in-depth knowledge of such processes helps Evonik develop new powders for a variety of printing techniques, says Diekmann. “Depending on the requirements, it takes us between six months and two to three years—sometimes even more—to create a new material.” Polyamide 12 (PA 12), which is used in innumerable applications, often serves as the basis to which the developers at Evonik give new properties with the help of additives. “Flame retardants, for example, make it suitable for use in the electronics industry or in components for aerospace applications,” says →

The US company Local Motors produces the shuttlebus “Olli,” which consists of 80 percent printed parts

“There’s still a lot of uncharted territory in the field of polymers”

SYLVIA MONSHEIMER, HEAD OF THE NEW 3D PRINTING TECHNOLOGIES MARKET SEGMENT AT EVONIK.

Diekmann. “And when a material has to be especially robust, we add glass particles, for example.”

The lab in Marl also creates completely new combinations of materials. Last year, for example, Evonik presented the high-performance powder PA 613, which combines the advantages of long-chain and short-chain polyamides. This powder is thermally stable, strong, and nonetheless flexible. Moreover, it absorbs little water. In 2018 the thermoplastic elastomer PEBA (polyether block amide), which was introduced in the 1980s, served as the basis for a powder that enables objects to be printed that have an almost rubber-like consistency.

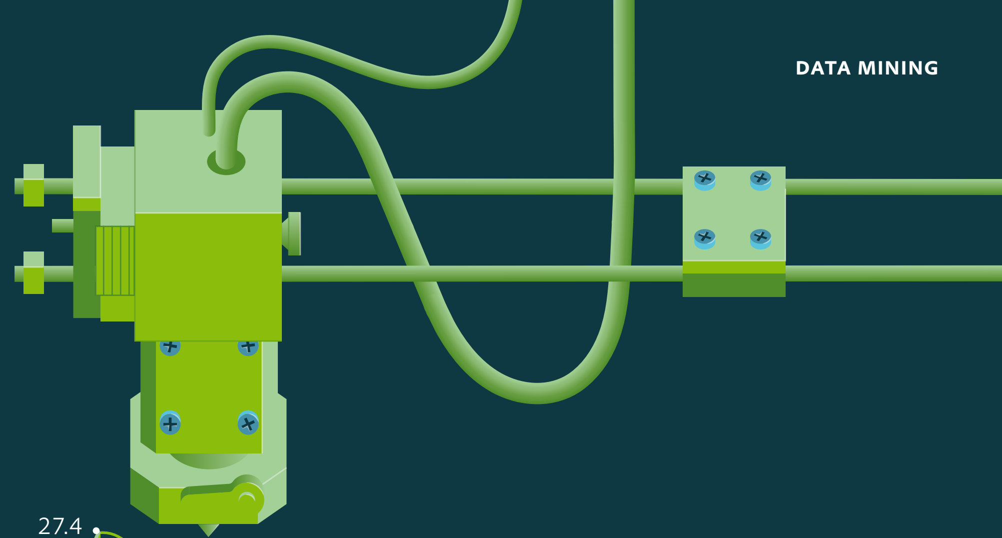
“No other company in the world has as many different powder manufacturing methods as Evonik,” says Grosse-Puppendahl. What’s more, many of the applications that are still not possible should be achievable with a new production technology that the company purchased in 2019. This process was developed by the US startup Structured Polymers and enables a lot more materials to be pulverized than Evonik could achieve before. The best example of this is a new copolyester powder, which was also the first material to be produced with this innovative technology.

POWDERS AREN’T THE ONLY PRINTING MATERIALS

The experts are also investigating other starting materials besides powders. Startups such as the Austrian company Cubicure (see the overview on page 14) and Creavis, the strategic innovation unit at Evonik, are working not only on powder-based processes but also on printing techniques in which the workpiece is drawn from a liquid photopolymer. Light sources such as lasers harden this light-sensitive material at the desired points. The precision is unparalleled, says Cubicure CEO Robert Gmeiner. “The resolution is only defined via the optical mask, which can be set with extreme precision,” he adds. Moreover, only ten percent of the starting material cannot be used for further printing after production. “Powder-based methods are a long way from achieving that.”

Other SLA-printing manufacturers are also working on the development of new materials in cooperation with the specialists at Evonik. Last year Evonik opened a new research hub in Singapore, where formulation specialists are developing next-generation photopolymers. “There’s still a lot of uncharted territory in the field of polymers,” says Monsheimer. But that is precisely why this work is so intriguing for Monsheimer and Diekmann. “Ever since I started to work here, I always wanted to get away from the principle of ‘One company, one process.’ I’m delighted that this is now happening,” she says.

EOS, which is based in Krailing near Munich, is cooperating with Evonik to offer various 3D printing systems



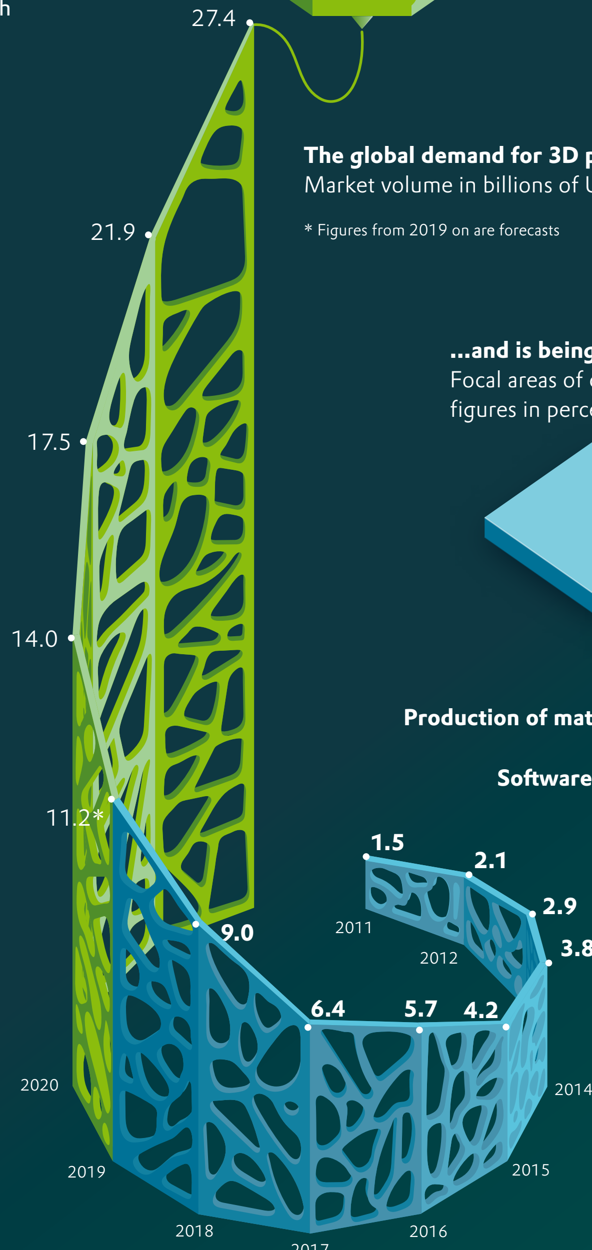
PRINTING SPREADS

Additive manufacturing has left its niche and is now expanding into the mass market. Where are the key players based and which materials and techniques do they use?

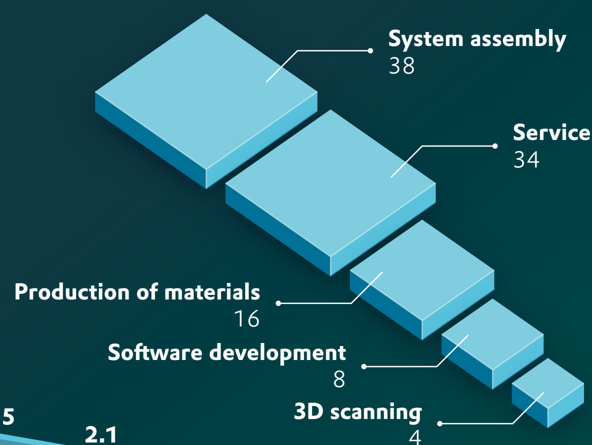
Sources: Ernst & Young Global Limited, Statista

The global demand for 3D printing is increasing...
Market volume in billions of US$ from 2011 to 2023

* Figures from 2019 on are forecasts



...and is being served by a variety of players:
Focal areas of companies in the 3D printing sector, figures in percent, 2019

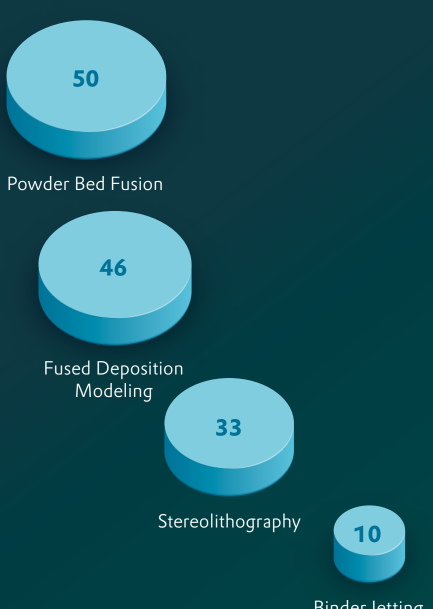


What you need for additive manufacturing: optimum materials...
The most commonly used materials for 3D printing at businesses: Percentages worldwide in 2018 (multiple mentions possible)

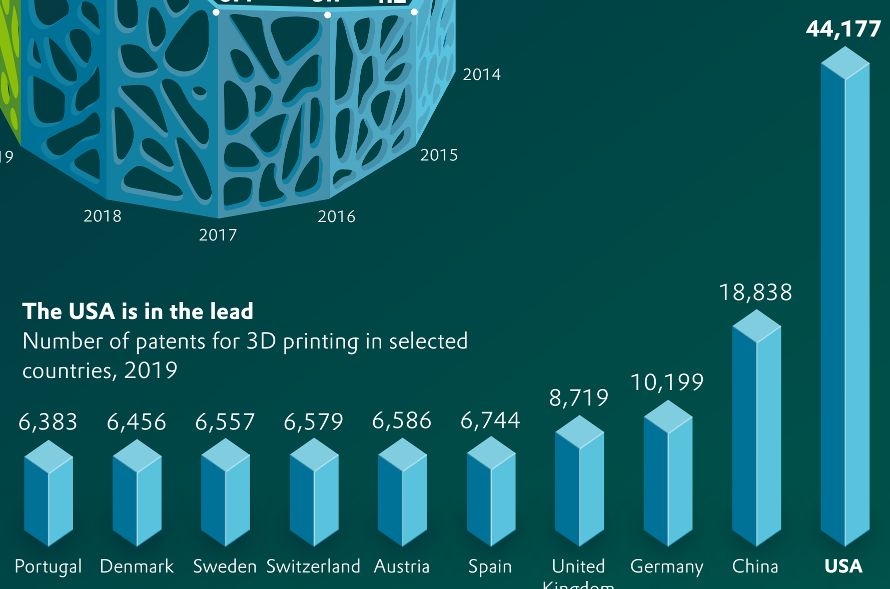
72
Plastic

49
Metal

...and appropriate technology
Selected 3D printing techniques at companies: Percentages worldwide in 2018



The USA is in the lead
Number of patents for 3D printing in selected countries, 2019



VERY CLOSE TO NATURE

Open to new things: Senada Schaack founded the SAM 3D innovation unit for 3D printing with metal at Evonik in 2018

Today Evonik is using 3D printing, along with other technologies, to construct its own production facilities. Metal powders are being used to build reactors and devices based on biological models. That's good for the environment—and for cost-effectiveness

TEXT **GEORG DAHM** PHOTOGRAPHY **RAMON HAINDL**

If you're not paying attention, it's easy to overlook the revolution taking place around you. Walk behind gigantic milling machines and past workshop cubicles where welding light flickers through rubber curtains, pass through a flood of sensory impressions consisting of hammering and the smell of metal, and you'll come to a glassed-in cubicle standing against a wall. You may enter it through the lock chamber only if you're wearing mouth protection. Behind the big windows, a technician is producing components made of metal powder in a 3D printer that is as big as a cabinet.

This method, which Evonik is using at the factory site in Hanau to develop and produce new reactors and components, is opening up entirely new opportunities for the chemical industry to shape its plants and processes. These opportunities include improving the plants' performance, reducing costs, and decreasing their environmental impact.

At his computer in front of the glassed-in cubicle, Daniel Adam is preparing a structure for printing that looks more like an anatomical model than the model of a machine. It's a construct made of pipes of various thicknesses that join together to form a larger structure which then again sprouts branches, similarly to the human venous system. Adam checks the construct layer by layer, planning in supportive networks at the spots where the slender pipes would otherwise buckle in the bath of metal powder. If you recognize models from the realm of biology in this machine component, you wouldn't be wrong. "We do in fact observe how nature optimizes structures such as capillaries, muscles, and roots," says Senada Schaack, who is responsible for 3D printing at the Process Technology and Engineering unit at Evonik.

OPTIMIZED FORM

Actually, Schaack was never especially interested in biology. In her home town of Sarajevo, she started to study mechanical engineering. Due to the war in Bosnia she ended up in Hanover, where she received a doctoral degree for her work on the simulation of multiphase flows. Later on she started to work at Evonik.

Her enthusiasm about the opportunities opened up by simulations eventually motivated her to propose that the Group establish a competence center for 3D printing in the production of apparatus for chemical processes. "When I combine the opportunities offered by 3D printing with those of computer simulation, I can find an optimal shape for apparatus that could not be implemented by using traditional methods," Schaack says. Since 2018 she has been doing research with a dozen colleagues in the facility she had visualized: the Simulation and Additive Manufacturing 3D competence center, or SAM 3D for short. They are finding out how to make reactors and components for the Evonik Group's chemical production facilities even safer and more efficient with the help of 3D printing.

Turning, drilling, milling, welding: Until now, these have been the technologies for making the reactors in which the chemical industry manufactures →

Senada Schaack (right) and her colleague Maninadh Podapaka

Printed test pieces for reactor development

its products. Chemists, process engineers, and mechanical engineers have used many innovations to make them highly productive and efficient. "If I can use simulations in combination with 3D printing to customize the shape from the very start so that I have optimal conditions at every point in the reactor, I need much less energy and less solvent or none at all, and I get higher yields," Schaack explains. "That way we can make a visible contribution to increasing sustainability."

DEVELOPING A PROTOTYPE IN TWO MONTHS

Greater sustainability—that is Schaack's motivation and her central idea behind the project. But this idea also offers tremendous economic potential, because the cost of development with the help of 3D printing is significantly lower than the cost of using conventional methods. "We printed a new construction in two days, and now we can test it, improve it, and test it again," says Schaack. In the future she plans to submit optimized prototypes within two or three months. That's the length of time that conventional methods sometimes require simply to create the first experimental structure.

Word of the possibilities that 3D printing offers for process development has spread quickly throughout Evonik. Inquiries and ideas are coming not only from Hanau and Marl, where the team operates, but from all over the Group. The SAM 3D team confers regularly with other Evonik locations, whether they are in Vancouver, Birmingham, or Singapore. At workshops conducted together with the Evonik business units, Schaack and her team explain their working methods and cooperate with their colleagues to find solutions for previously unsolved problems.

A BLOOD VESSEL? OR A REACTOR FOR A CHEMICAL PLANT?

The group headed by Schaack is relatively young, but older colleagues also see the technology's potential. Their reaction can be summed up in one word: "Finally!" Finally it's possible to implement ideas that in some cases have existed for decades without being technically feasible. "In the workshops we start talking about topics such as microreactors—topics that emerged around 2000 but were then shelved," says Johannes Ehrlich, the head of the special plant construction unit at Evonik. "Today these topics are sparking interest once again."

The delicate structures that Schaack's team can calculate and print make it possible to solve traditional challenges in chemistry, such as the tremendous amounts of waste heat that are generated by many reactions. "In exothermal processes of this kind, we sometimes see the formation of hotspots that are harmful for the product and also for the plant," says Andreas Gumprecht. Together with his colleagues, he is clicking his way through a simulation model that was calculated via the SAM 3D process. "With the help of this method, we can develop apparatus for challenging reactions of this kind—apparatus with geometries that ensure an improved heat exchange process," he concludes.

The interior of a demonstration piece printed from steel

Plant operator David Fuchs wears a protective suit to fill a printer with metal powder

LESS EFFORT, MORE CONTROL

The new production technology is still in its initial phase. “It’s not a substitute for traditional plant construction—it’s a complement to it,” says Ehrlich. However, he adds that printed reactors already bring “smoother operation into the system” because they have fewer individual parts, require less maintenance, and enable more monitoring. “A reactor usually has one temperature measurement and one pressure measurement,” Ehrlich explains. “Now we are planning to incorporate 16 sensors, and we’ll be able to acquire much more data.” In the past, it was not possible to fit so many sensors into a narrow space by means of traditional production processes. Thanks to 3D printing, it’s now possible to print the access points for sensors directly along with the component.

3D-printed reactors are already proving their worth in the first set of production facilities at Evonik. However, most of the unit’s projects are still in the laboratory—or in the pilot phase, according to Schaack. This is mainly because reactors printed from stainless steel powder are still a novelty in the chemical industry. These components must be certified according to their respective areas of application. “Because there were still no standard requirements in this area and we didn’t want to wait until they existed, we took matters into our own hands. Together with the Technical Inspection Agency TÜV, we developed the certification process,” says Ehrlich. After the successful TÜV certification, Evonik is now one of the first companies that is permitted to produce metal pressure reactors by means of additive manufacturing methods.

DELICATE STRUCTURES MAKE NEW PROCESSES POSSIBLE

Schaack and her team are using the top quality of these processes and products to advertise their services. In the next three years, they want to shorten the period of time from the initial idea to its implementation on the production line—but that’s not all. “Now that we’ve set up all the basic principles and the entire process chain, we want to offer our know-how to the entire Evonik Group and its customers as a development platform,” says Schaack.

After all, they don’t want to limit the revolution to Hanau and Marl alone.

Prof. Wai Yee Yeong (42) is the Program Director at the Singapore Centre for 3D Printing (SC3DP), one of the most important research institutes for additive manufacturing in Southeast Asia. She has been working on 3D printing since 2004 and is one of the leading researchers in this field. She was honored with the TCT Award in 2019. This international award recognizes female innovators who are driving the development of 3D printing technologies

"We can improve patients' quality of life"

Wai Yee Yeong is a researcher in Singapore who is studying the production of human tissue with the help of bioprinters. This process could not only speed up drug tests and make animal testing unnecessary—but also revolutionize transplantation medicine

INTERVIEW **CHEERIO CHAN**
PHOTOGRAPHY **NORMAN NG**

Professor Yeong, in your research you have been interested in every possible kind of 3D printing. Why are you so fascinated by bioprinting in particular?
I want to develop bioprinted constructs that can ultimately replace organ transplants from donors. In this way we can improve patients' quality of life. Bioprinting is the technology that will make tissue engineering possible in the first place. But even before we can do that, we can use this technology to produce in vitro models that reduce animal testing and improve the predictability of therapeutics testing.

How does this technology work?
Bioprinting is 3D printing that uses cells and scaffolding biomaterials as inks. The biomaterials are used to construct the scaffolding. By using a bioprinter, we can precisely position the deposition of cells and biomaterials. This gives us the ability to design the optimal 3D environment for cell growth, develop new strategies for cultivating different kinds of cells and materials together, and manipulate the shape of cellular constructs.

Which organs can theoretically be printed using bioprinters?
Recently I have concentrated my research on skin, retina, and lungs. I have also been working together with hospitals to develop new solutions. For →

“Currently we can already print two-dimensional tissues such as skin”

An all-rounder: In her work, Yeong deals with a wide spectrum of disciplines, ranging from materials science to medicine

example, I looked at how the pancreas can help us gain a better understanding of diabetes. All of the projects that I am currently working on require different design methods and different formulations of materials.

Lungs from a printer—that sounds like a dream of the future. How far has this technology been developed to date?
We are at a very exciting stage right now. Currently we can already print two-dimensional tissues such as skin, as well as thin tubular structures that are used for the in vitro testing of drugs and toxic compounds.

What are the biggest obstacles that hinder the development of more complex applications such as tissue and organ transplants?
One of the major challenges to overcome is the supply of nutrients. That’s why we are looking into the cultivation of vascular tissue. On account of the resolution of current bioprinters, we’re starting with small blood vessels. Another obstacle that has hindered the development of organ printing so far is the limited number of materials that can currently be used as inks. For bioprinting we require soft gel-like materials that promote the growth and migration of cells. However, these materials do not have the mechanical integrity to retain the shape we desire, so we need to develop strategies for enhancing their mechanical integrity. We also need biomaterial inks or additives that promote the interactions between the host tissue and the graft tissue, so that the printed organ will be successfully integrated with the patient’s tissue following the implantation.

How are you working together with Evonik in this area?
Among other things, we are co-mentoring a Ph.D. student who is focusing on the area of bioink. In order to enable the printing of larger biological constructs, we need a greater selection of inks that have varying material characteristics. For extrusion-based bioprinting techniques, smart materials that respond to specific stimuli are of interest.

When will you start to produce the first organs?
That process still has a long way to go. We need to use a lot of cells, and this requirement increases with the size of the tissue construct and the scale-up of the application. This obstacle is compounded by the challenges and concerns related to the use of primary cells that are isolated directly from patients. To address this problem, we are currently investigating the use of induced pluripotent (adult) stem cells. We are still at an early stage of integrating stem cells and bioprinting in order to expand the overlapping applications of these two areas. Another challenge is the nutrient solutions that are needed. We require “universal” cell culture media to support the printed constructs that consist of multiple cell types. Currently most cell culture media have been optimized for only one or two types of cells.

Do you see these obstacles being overcome in five to ten years’ time?
I think it is possible for skin, because its structure is less complex. This applies in particular to tissue models, particularly tissue constructs that do not require a lot of

Elements reporter Cheerio Chan (at right) met Wai Yee Yeong on the campus of Nanyang Technological University

support from blood vessels, such as cornea and retinal layers. Large-diameter blood vessel grafts will probably become available as well. For organs with a complex structure and a high level of functionality, such as the liver and neural tissue, we will need to incorporate significantly more biological inputs.

In your opinion, what possibilities are opening up for 3D printing in general in the field of medicine?
Right now, the best results we can achieve are implanted medical devices that are produced on a 3D printer. However, these implants are not true replicates of the original tissue. I believe that bioprinting will provide us with the tools, platforms, and financial resources that we need in order to cultivate a truly biological construct that can be substituted for the original organ. We also want to create bionic organs that combine living and non-living materials. Such constructs might function even better than a fully biological construct.

Why is so much know-how in the area of bioprinting technology concentrated in Singapore?
I believe that we occupy a strong leadership position in the field of 3D printing in Asia and globally. At the research level, we have strong support from the government—for example, we have one of the best-equipped university research labs in the region. This strong foundation is very closely integrated into the overall research landscape in Singapore, particularly in the area of biosciences. In addition to our research partnerships with universities and research institutes, we also work with technology companies such as Evonik and HP Inc. to look for solutions that address real industry needs.

THE DIRECT ROUTE

TEXT **HANNS-J. NEUBERT**

Evonik has developed a new process for the efficient and environmentally friendly production of propylene glycol. In cooperation with the US-based Dow company, the technology is now being brought to market maturity

Sometimes you need to take a backward look before you can really move a project forward. In 2012 Holger Wiederhold, a researcher in the Active Oxygens Business Line at Evonik, came upon a note that had been entered in a database years ago. Bernd Jaeger, who was at that time a Head of Research at Evonik, had recorded his thoughts about the direct synthesis of propylene glycol. He had speculated that this coveted product, which was normally manufactured in several complicated steps via precursor products, could be synthesized in a single step that offered major benefits.

But back then Jaeger had not come up with a practical approach to a solution, so he merely left a note about his project in the in-house database. In this memory bank of ideas, Evonik researchers save suggestions for which they don't yet see a possible technical implementation, but which they hope will someday be found by someone.

While Wiederhold, a chemist, was reading Jaeger's note, he suddenly realized how this chemical synthesis could work. "That was the starting point of HYPROSYN™," he says. The project for developing the cost-effective and sustainable direct synthesis of propylene glycol has been conducted by the Active Oxygens Business Line in the laboratories of process technology since 2013.

The demand for propylene glycol is huge, and it's growing by 2.5 percent annually. This compound is used in antifreeze, lubricants, fiberglass-reinforced plastics, cleaning and washing products, and latex wall paints. It's also indispensable for the food industry. It gives chewing gum the right consistency, makes baked goods soft, and keeps packaged foods moist. Livestock farmers use it to treat metabolic disorders of their dairy cows. "Propylene glycol has developed into an all-round bestseller," says Thomas Bode, who is responsible for HYPROSYN™ technology at Evonik. Today about two million tons of propylene glycol are processed annually worldwide. In order to meet the growing demand, developers have been working for years to find new solutions.

A PRECURSOR PRODUCT FOR MANY APPLICATIONS

At Evonik, a core team of four colleagues set out to develop a new process for synthesizing propylene glycol. "In order to refine this process, we needed the support of additional colleagues from a whole range of different areas," explains Wiederhold. Many colleagues from all over the Group contributed their know-how to this development process.

Previously, the first step in the production of propylene glycol had often been the production of propylene oxide. In order to manufacture this precursor product, Evonik cooperated with thyssenkrupp from 2000 on to develop the HPPO process. This acronym stands for "Hydrogen Peroxide to Propylene Oxide." In 2008 this process was licensed for the first time for a production plant in South Korea, which today is turning out more than 130,000 tons of propylene oxide annually. By contrast to traditional synthesis methods, which require substances such as chlorine or benzene, this process requires only propylene and H_2O_2, which is supplied by Evonik. The only byproduct of the process is water.

The intermediate product propylene oxide is in high demand. One fifth of the total production volume is used to synthesize propylene glycol. Two thirds of →

From veterinary medicine to aeronautics, the applications of propylene glycol are wide-ranging

> **“Propylene glycol has developed into an all-round bestseller”**
>
> THOMAS BODE, HEAD OF PERFORMANCE OXIDANTS AT EVONIK

the total production volume are processed into polyether polyols, which are then processed via intermediate steps into polyurethane (PU) products such as construction foams and paint bases. The remaining propylene oxide is used as a starting material for producing other valuable chemicals. The demand for propylene oxide has recently grown even faster than that for propylene glycol, by about four percent to approximately 11 million tons.

One way to continue meeting this demand in the future would be to build additional propylene oxide production plants. However, each of these plants would cost hundreds of millions of euros. Alternatively, researchers could search for innovative solutions that simultaneously open up new applications for environmentally friendly hydrogen peroxide. “We considered the second alternative much more attractive,” says Wiederhold, who headed the project.

The key to success, which helped Wiederhold achieve a breakthrough, was a newly developed catalyst system. Thanks to this, it is now possible to generate propylene glycol in a single reaction between propylene and hydrogen peroxide—without the intermediate step of propylene oxide. In general, a catalyst system makes a chemical reaction easier and faster. The special charm of this particular solution is that some of the components of the new catalyst were already used in other chemical processes at Evonik. “The combination of different input materials, together with special technical processes, ensures that the catalyst remains stable over a long period of time,” says Wiederhold. “In addition, it transforms the basic materials propylene and hydrogen peroxide in a process that is especially efficient and energy-conserving.”

EXPERIENCE WITH H_2O_2 PAYS OFF

As a result, the HYPROSYN™ process is not only more cost-efficient than the previously used technology; it also makes a significantly higher yield possible while requiring much less energy. As with HPPO synthesis, except for water there are no other coproducts that would have to be separated out. Now that the process has functioned superbly in the laboratory, it is being scaled up in a pilot plant with a capacity that is 160 times bigger. Instead of the lab’s output of 50 grams of propylene glycol per hour, the pilot plant will produce eight kilograms an hour. Construction of the plant in Hanau will be completed in 2021. “It will then be operated for one year in order to improve the process and verify the results,” says Evonik manager Thomas Bode. HYPROSYN™ is expected to reach market maturity in 2022.

The success of this new product is due in large measure to Evonik’s experience with peroxide chemistry, which goes back for more than a century. H_2O_2 is one of the Group’s most important sales products. It is used in numerous applications. Initially it was mainly used as a bleach for textiles and paper, as well as a disinfectant. Today it is used, among other things, in the electronics industry to clean printed circuit boards and semiconductors for the manufacture of LCD displays. In rockets, hydrogen peroxide drives the turbopumps that force the actual fuel into the combustion chambers. HYPROSYN™ technology is now opening up an additional sales market.

Evonik is a leading supplier of H_2O_2 with 18 production sites and an annual global capacity totaling more than one million metric tons. The Group has established itself primarily as a specialist in the production of highly concentrated hydrogen peroxide. The HPPO synthesis process that has by now become familiar uses 70-percent H_2O_2. Conventional processes use concentrations of 50 percent or less. Evonik can even deliver H_2O_2 at a concentration of 98 percent—a top value in the industrial production of hydrogen peroxide.

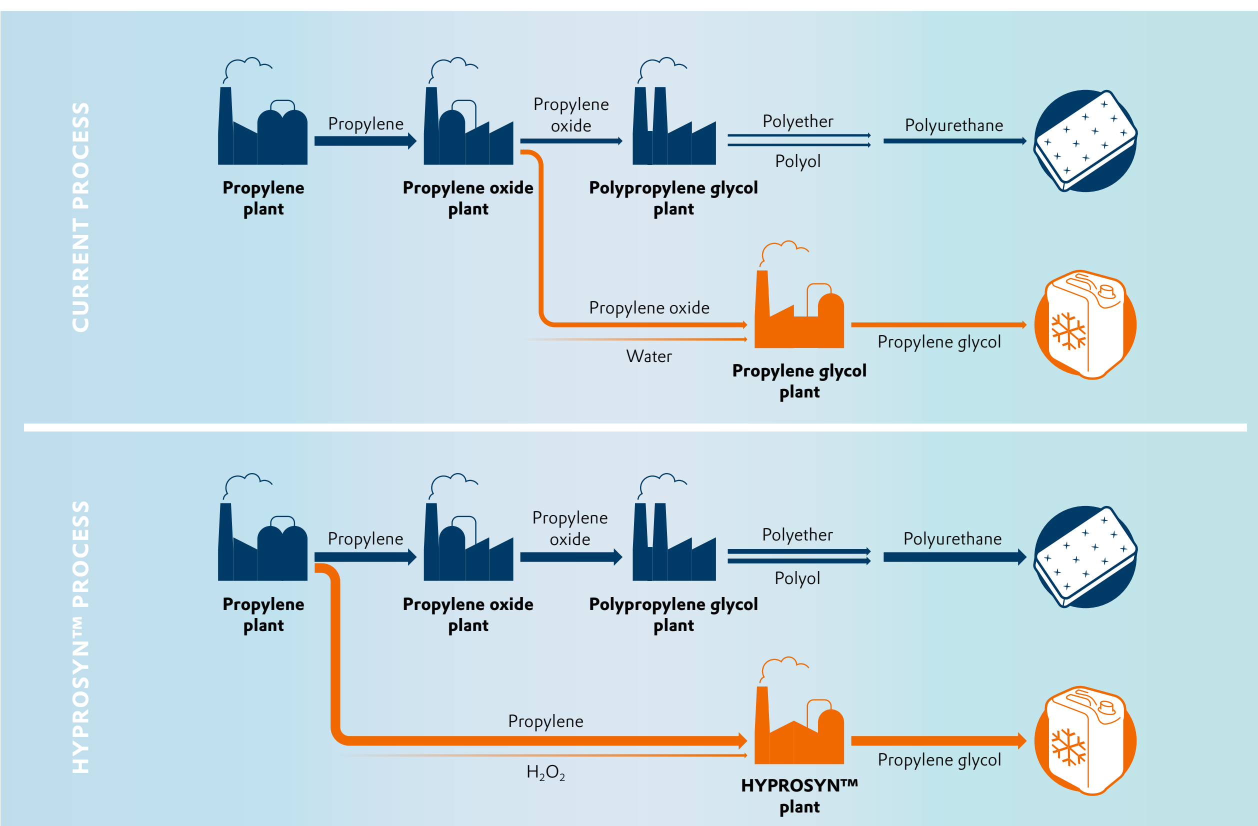
A NEW LIFE FOR OLD PLANTS

But the advantages of this new process go even further. That's because the chemical reaction of propylene and hydrogen peroxide that has just been described takes place in one single reactor. That makes the previous precursor product, propylene oxide, unnecessary. Through the economical conversion of existing propylene glycol production plants to HYPROSYN™ production, the propylene oxide that was previously needed can now also be used as a basic material for PU products. The new technology can thus be regarded as a smart method for indirectly expanding the capacity of propylene oxide production plants. In addition, the introduction of HYPROSYN™ technology makes it possible to manage the production of propylene glycol and of propylene oxide independently of each other. As a result, the production volumes of these two materials can be more easily adapted to the demand.

Evonik is now working together with Dow to refine the new technology to the point of market maturity. The US company Dow produces propylene glycol and propylene oxide in many plants on four continents and is the global market leader for both products. Michael Träxler, the head of the Active Oxygens Business Line, calls Dow an "ideal partner"—largely because of its expertise in the area of materials science.

"For us, it's important that the new technology fulfills the stringent quality criteria for medical applications in particular, so that it offers a competitive alternative to existing processes," says Meinolf Weidenbach, the Technology Leader PO/PG Technology Center at Dow Deutschland. Vincent Lacoste, the Global Business Director at Dow for sales of propylene oxide and propylene glycol, hopes that this partnership will create a competitive advantage for his company's own products. "Thanks to the HYPROSYN™ process, we can offer a cost-efficient product based on a sustainable and environmentally friendly technology, which will help us to be more flexible as we support our customers," he says.

Once the HYPROSYN™ process and the associated reactor technology are ready for industrial-scale production, Evonik and Dow also want to license it to third parties all over the world. And that's how an idea in a database will ultimately become a profitable business.



A lean process
The HYPROSYN™ process frees up facilities that produce propylene oxide

Christian Kullmann is the Chairman of the Executive Board of Evonik

Engineers of the Future

by Christian Kullmann

Economic success and environmental protection are not mutually exclusive. On the path to a sustainable economy, we don't need new restrictions or symbolic sacrifices. We need more innovation. And when it comes to innovation, our company is an outstanding source

In the social networks, on the street, and of course in the media, the public debate about climate change and the climate crisis is ever-present—and it is being conducted across increasingly hardened fronts. But its common denominator is the smallest conceivable one: All of us naturally want to preserve a livable planet for our children.

But instead of conducting the discussion with objective arguments, people are conjuring up a struggle between nature and industry. That isn't the right way forward. At best, it leads to symbolic actions and global competitive avowals. These in turn corrode public trust in politics and industry in equal measure. And they are counterproductive, because the chemical industry in particular is a key factor in the effort to better protect our climate.

“There should be no contradiction between environmental protection and sustainability on the one hand and growth and profitability on the other”

We don’t need repeated restrictions and more and more sacrifice. We need policies that optimally promote innovations. If we here in Germany don’t demonstrate that protection of the climate and the environment goes hand in hand with economic growth and social well-being, we’ll be the losers. In any case, the goals of the Paris climate agreement cannot be achieved without the chemical industry. No wind turbines can spin without our technology, and no electric cars can drive without our products. We are the engineers of the future.

EVONIK IS THE DRIVING FORCE

Those who continually preach sacrifice and aim to achieve change through restrictions will never be global pioneers. Whereas the community of nations is still discussing climate protection measures, many companies have long been taking action. At Evonik we want to be the drivers of solutions for urgent future-related issues. We are therefore systematically implementing our strategy for climate change and sustainability. The goal we have set for ourselves is more ambitious than the German government’s plan for Germany as a whole. Evonik aims to cut its absolute emissions in half in the period between 2008 and 2025, while significantly boosting our sales by manufacturing sustainable products.

Today, products whose application demonstrably leads to greater sustainability and improved resource efficiency already account for more than half of Evonik’s sales. Additives from Evonik make wind turbines and solar panels highly efficient and durable. Silicon dioxide from Evonik improves heat insulation in buildings. Materials from Evonik that are used in separators and cathodes make batteries for electric cars safer and more efficient.

MAKING CO_2 USEFUL

The chemical industry needs massive amounts of energy. But switching our energy supply completely to CO_2-neutral electrical energy would be only theoretically possible. In reality, “green” energy is neither available nor affordable in the amounts that chemical production processes need. That’s why we’re working on alternative solutions for our own processes and our customers’ products, as well as answers to the question of what should happen to CO_2 emissions.

We want to not merely reduce CO_2 emissions but to make them useful as a raw material. In cooperation with Siemens, Evonik is researching electrolytic and fermentation processes that make artificial photosynthesis possible. In this context we are producing chemicals with the help of CO_2, “green” electricity, and bacteria. This is a technology that in the future could be set up wherever CO_2 is generated.

Investments in research and development are just as essential as partnerships across sector boundaries. People who celebrate the companies that sell electric cars while demonizing the sector that makes the production of these cars possible are lacking in the vital understanding of value chains.

Customers and investors are demanding that we grow. Besides, we can only hold our ground in global competition if we grow and are profitable. That’s why there should be no contradiction between environmental protection and sustainability on the one hand and growth and profitability on the other. The good news is that they are mutually compatible. Sustainability has always been our business. Thinking in terms of the future has always meant taking our environment into account just as much as the well-being of our children and grandchildren. We have to factor in not only the environmental aspects of transformational processes but also their social acceptability. That’s because genuine sustainability is only achieved when our planet, people, and the economy ultimately benefit in equal measure.

TOGETHER TO THE GOAL

Through our areas of expertise we can make a huge contribution to a more sustainable future. But as long as not enough “green” energy is available at competitive prices, and as long as we are still researching the use of alternative raw materials, we reject dictates and dividing lines. We need the trust of the public as well as support from political decision-makers. Only if we work together will we succeed in making sustainable business operations even more attractive through innovations—and leaving a livable planet behind us for future generations.

A Young Nation with a Long Tradition

Slovakia is a small country, but its citizens are hugely enthusiastic about their homeland, including its popular sport of ice hockey, its natural landscapes, and its rebounding automotive industry

TEXT **ANNA SCHRIEVER**

There are more than 200 castles and palaces in Slovakia, a country that is smaller than the state of Bavaria. One of the best-known is Bratislava Castle, which towers high above the country's capital of the same name and dominates the cityscape.

“Slovenskoo, heja, heja, heja, Slovenskoo”—that was the battle cry of the Slovakian fans who cheered their team to victory in the ice hockey World Cup in 2019, which was held in their home country. Ice hockey is Slovakia’s national sport. Fans are thrilled by the incredible dynamism and fast tempo of this hard-driving sport. The players can accelerate the puck to speeds as high as 170 kilometers per hour. The fact that the hockey sticks don’t break in the process and the players remain in full control is due to ROHACELL® from Evonik. But this high-performance foam can do even more: It also absorbs the impact energy. That enables the players to control their game more effectively and speed up the pace even more.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KRUSO
Berger

The automotive sector is the backbone of Slovakia's economy. The country produces over one million vehicles per year. That's about 190 vehicles per 1,000 inhabitants—more than any other country in the world. The automotive sector accounts for 44 percent of Slovakia's total industrial production and 40 percent of its industrial exports. More than 145,000 jobs directly depend on this sector. Automotive coating additives from Evonik not only give the vehicles a glamorous sheen but also provide them with long-term protection. Rough treatment leaves no marks, and raindrops simply bounce off.

With nine national parks, the majestic peaks of the Carpathian Mountains, and mysterious ravines, Slovakia is a paradise for hikers. About 40 percent of the country is covered by forests. Visitors who want to explore these natural landscapes must be able to rely on their equipment. Through its innovative plastics solutions, Evonik is bringing more sustainability into the sports industry. The bio-based polyamide VESTAMID® Terra is popular not only because of its environmental advantage but also because it protects equipment from impacts and cracking due to cold and wet weather. That's why it's ideal for items such as all-weather buckles on hiking rucksacks.

Every region of Slovakia is proud of its own folklore. Whether it’s traditional costumes, music, customs, dances or dialects, many traditions have been preserved until the present day and are on show at folk festivals. Traditional hairstyles are part of the picture. Evonik’s RHEANCE® One is a contribution to gentle and effective hair care. The fermentation process that is required for the production of RHEANCE® One takes place at the Evonik facility in Slovenská Ľupča.

SUSTAINABLY SUCCESSFUL

Since 1993, Slovakia has been a key location for Evonik's industrial fermentation processes for new products. The trend toward sustainability, whether it's in animal nutrition or in the cosmetics industry, has benefited the facility in Slovenská Ľupča. Recently the Group has also begun to cooperate with the startup Modern Meadow on activities there for the production of artificial leather.

Evonik locations
1 Bratislava
2 Slovenská L'upča

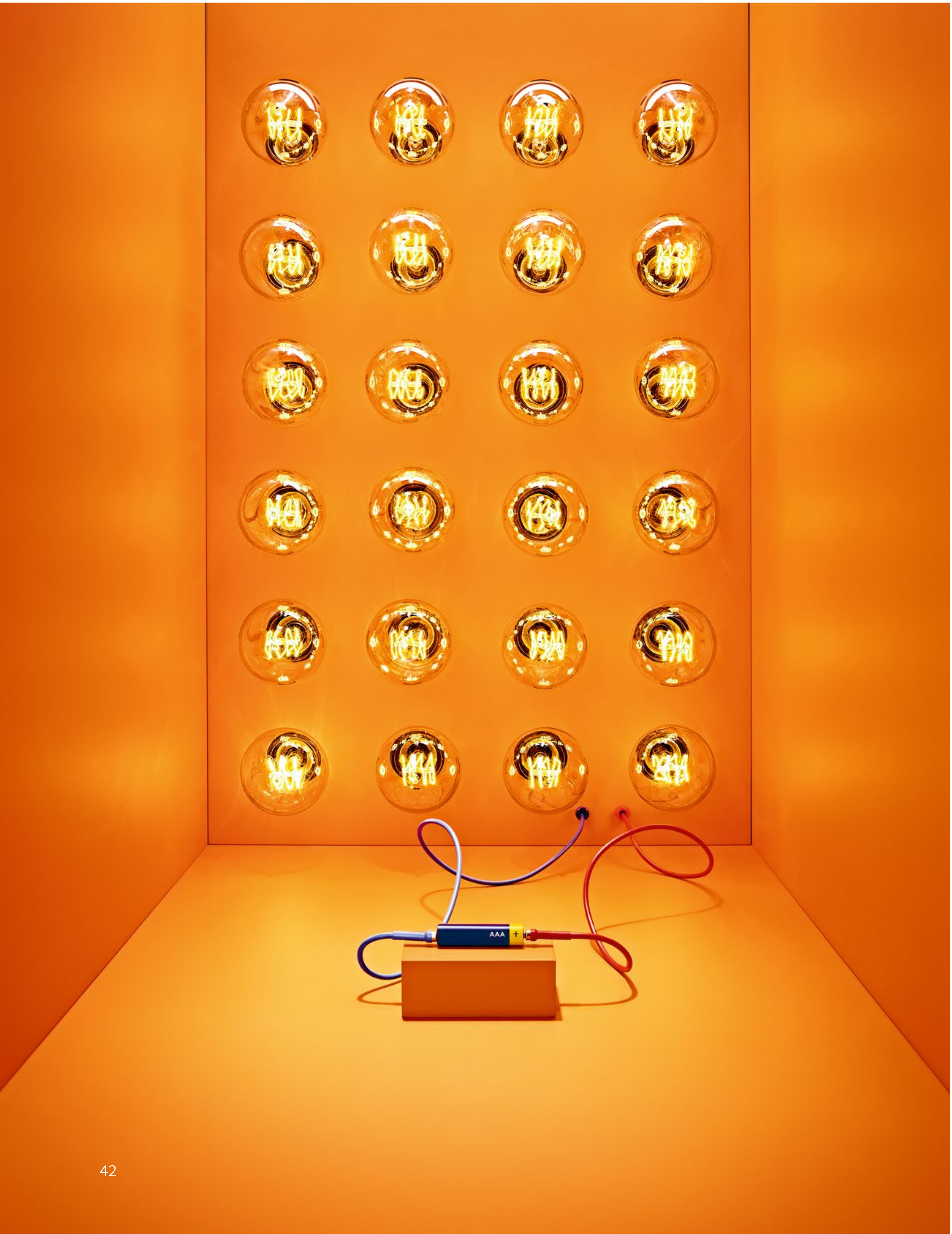
The

2

Evonik locations have

230

employees.


AAA

CHARGED AND SAFE

TEXT **TOM RADEMACHER**

Improved batteries are playing a key role in the energy transition and in sustainable mobility. Evonik is working to make energy storage systems more efficient and cost-effective. Even well-known technologies have substantial amounts of potential that is still untapped

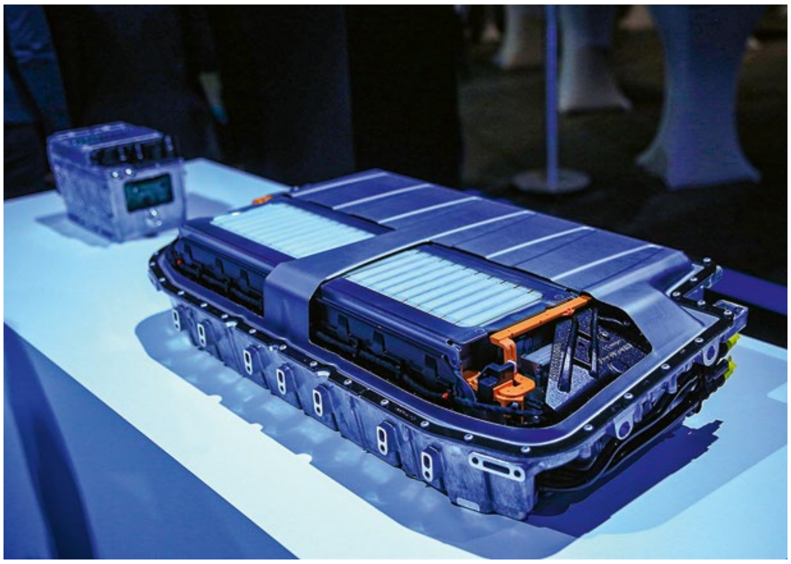
The *New York Times* doesn't often carry reports about the small town of Arnstadt in the German state of Thuringia. And if it does, it's because a young man named Johann Sebastian Bach was the town's organist three centuries ago. But since the summer of 2018, a very different star has attracted international media attention to this provincial town: This is where the Chinese company Contemporary Amperex Technology Limited, or CATL for short, is building its first battery factory outside China.

CATL, the world's biggest producer of batteries for electric cars, plans to invest two billion euros in this facility. The cornerstone has been laid, and the first rechargeable batteries for BMW cars will roll off the assembly line this year. BMW has ordered batteries costing a total of €1.5 billion. Up to 2,000 new jobs are to be created, and a decommissioned rail freight depot is being reactivated specially for CATL. "People are happy that a company that will offer jobs for their children and grandchildren is setting up a plant here," said the local director of Germany's federal employment agency to a *New York Times* reporter. Arnstadt residents are setting high hopes on battery technology.

And in this they are not alone. Energy storage systems have the potential to fundamentally change our economy and our society. Electric mobility, renewable energy sources, information technology, consumer electronics—just about every area of our lives depends on efficient energy or heat storage systems. These systems range from pumped storage plants that balance out the performance peaks of solar, wind, and hydroelectric power plants to dual-layer capacitors in electric cars' braking systems and electrolytic processes for generating energy-rich hydrogen from electricity (see the diagram on pages 50/51).

A CONSTRUCTION PRINCIPLE FROM THE 1990S

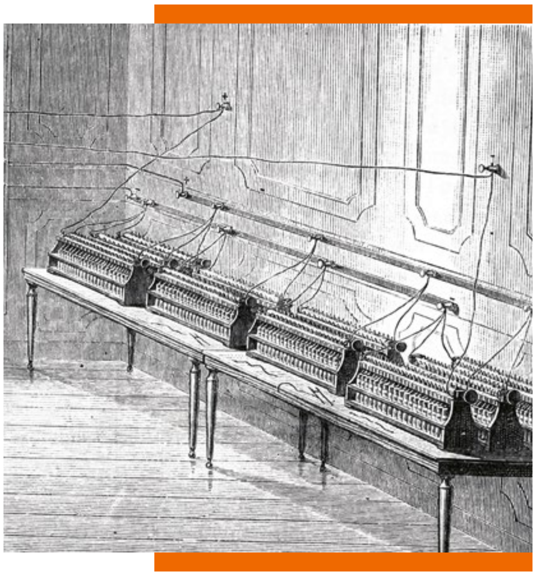
These systems' market opportunities are huge. During this decade, the automotive sector alone will invest US$300 billion in the development of electric vehicles, according to the Reuters news agency. The International Energy Agency (IEA) estimates that as many as 44 million electric cars may be sold worldwide in 2030. The forecasts of the French consulting company Avicenne Energy are much more conservative, but even it has predicted that the market for lithium-ion bat- →



Power pack Hybrid batteries for cars must be compact and deliver large amounts of energy within a short time

"The principle underlying the lithium-ion battery has not changed since the 1990s"

FRANK MENZEL, DIRECTOR APPLIED TECHNOLOGY SOLUTIONS AT EVONIK



The first lead batteries (based on the lead-sulfuric acid-lead dioxide system) were used around 1850—for telegraphic experiments, for example

teries in electric vehicles will almost quadruple over the next ten years to more than US$120 billion.

There are good reasons why modern lithium-ion batteries (or LIBs for short) play a key role in electric mobility: They are more high-powered and more efficient than anything that has come before. Their suitability for daily use is due to three inventors who received the Nobel Prize in Chemistry in 2019 for their work in this field (see the box on page 48). Even decades ago, lithium-ion batteries set the technical standard.

"The principle underlying the lithium-ion battery has not changed since the 1990s," says Prof. Frank Menzel, who teaches at the Technical University Ilmenau and is responsible for application technology for special oxides at Evonik. Menzel's statement might sound heretical to some. After all, developers have worked for three decades to lengthen lithium-ion batteries' service life, increase their capacity, and decrease their production costs. Between 2010 and 2019 alone, the price per watt-hour of storage capacity was reduced from one US dollar to less than 16 US cents. However, current LIBs basically still replicate the original structural design: The cathode consists of a lithium metal (mixed) oxide, and the anode is made of carbon. The cathode and the anode are kept apart by a thin separator, and all of the cell's components are soaked in a liquid electrolyte.

EVER STRONGER, EVER CHEAPER

In order to coax even better performance out of this established technology, Evonik is tinkering with almost all of its components. The goal is to achieve higher capacity, longer service life, and improved safety. And the road to this goal runs through the town of Rheinfelden near the Swiss-German border. This is where Evonik produces nanostructured particles of aluminum oxide and titanium dioxide. These particles could solve a whole series of problems, explains Dr. Daniel Esken, the head of the Application Technology Batteries unit at the Hanau location. Esken is also responsible for the battery projects conducted by the Silica Business Line at Evonik. "One of the challenges we face is the cathode material's reactivity with the liquid electrolyte," he says. "Undesirable reactions occur at this interface as a result of electrochemical processes as well as the high cell voltage." He points out one such reaction on an image that was captured with an electron microscope. Here the round cathode particles, which initially looked somewhat like shortbread cookies, have partially

A fine piece of work At the Applied Technology unit in Hanau, Evonik demonstrates how separator films are provided with a ceramic coating

disintegrated after 250 charging cycles and literally crumbled. This disintegration over time irreversibly reduces the battery's total capacity.

THE MIRACLE CURE: ALUMINUM OXIDE

This effect can be significantly limited if the cathode particles are coated with aluminum oxide or titanium dioxide. In the coating process, the nanostructured oxidic powder is mixed with the component material of the cathode. The powder coats the particles, and in the finished battery it reacts with the electrolyte to form a sort of glaze that allows ions to penetrate it but prevents the particles from disintegrating.

A brutal test clearly shows the beneficial effect of aluminum oxides on the separator in a lithium-ion battery. Behind a sheet of bulletproof glass, nails are driven through two battery cells. The first battery cell explodes, but the second one doesn't—thanks to the aluminum oxide in the separator. "During the extrusion process our material can be incorporated into the plastic or, alternatively, it can be applied as a thin ceramic coating onto the separator film," Esken explains. The porous separator is only about 20 micrometers thick—that's less than the diameter of a human hair.

Esken's team is also working with Hanyang University in Seoul on the use of aluminum oxide in electrolytes—in combination with methacrylate as a functional group on the surface of the oxide particles. "Our material is applied onto the separator as a ceramic layer, and it polymerizes with additives in the electrolyte after the cell has been filled," says Esken, the battery expert. Through this process, a gel is formed. This not only prevents the LIB cell from leaking but also improves the adhesion between the cell's components.

Not far from Esken's office, Dr. Julia Lyubina from the Strategy & New Growth Business Unit is focusing her research on the anode. She too is using a helpful product from Rheinfelden, in this case a completely new one. "Today's anodes consist of graphite," explains Lyubina, a materials physicist. "But we know that if we integrate additional silicon into the anode we can significantly increase its capacity." Unfortunately, there's a problem: When silicon particles are charged with lithium ions, they can swell up to as much as 300 percent of their previous size. That can burst the anode; worse yet, the particles disintegrate all over again. In order to solve this problem, Lyubina's team has developed an innovative composite material along with its own production process. The spherical particles that are used in the anode are about 200 nanometers in diameter. They consist of silicon and carbon, with the silicon mainly filling up the core and the concentration of carbon increasing toward the surface of the particle. "If ten percent of the anode's weight is made up of silicon, we can double its ion capacity," explains Lyubina. Until a few years ago, Evonik's Rheinfelden location was →

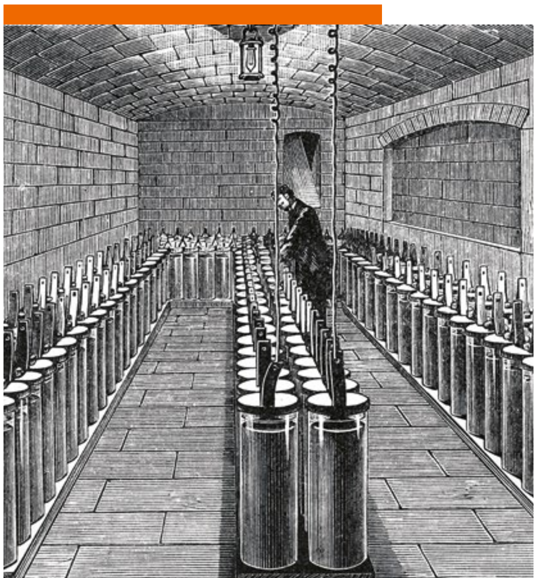
still producing pure silicon for the solar industry. An existing installation has now been converted to make the new product and is due to start pilot operation this year.

AN OLD TECHNOLOGY WITH POTENTIAL

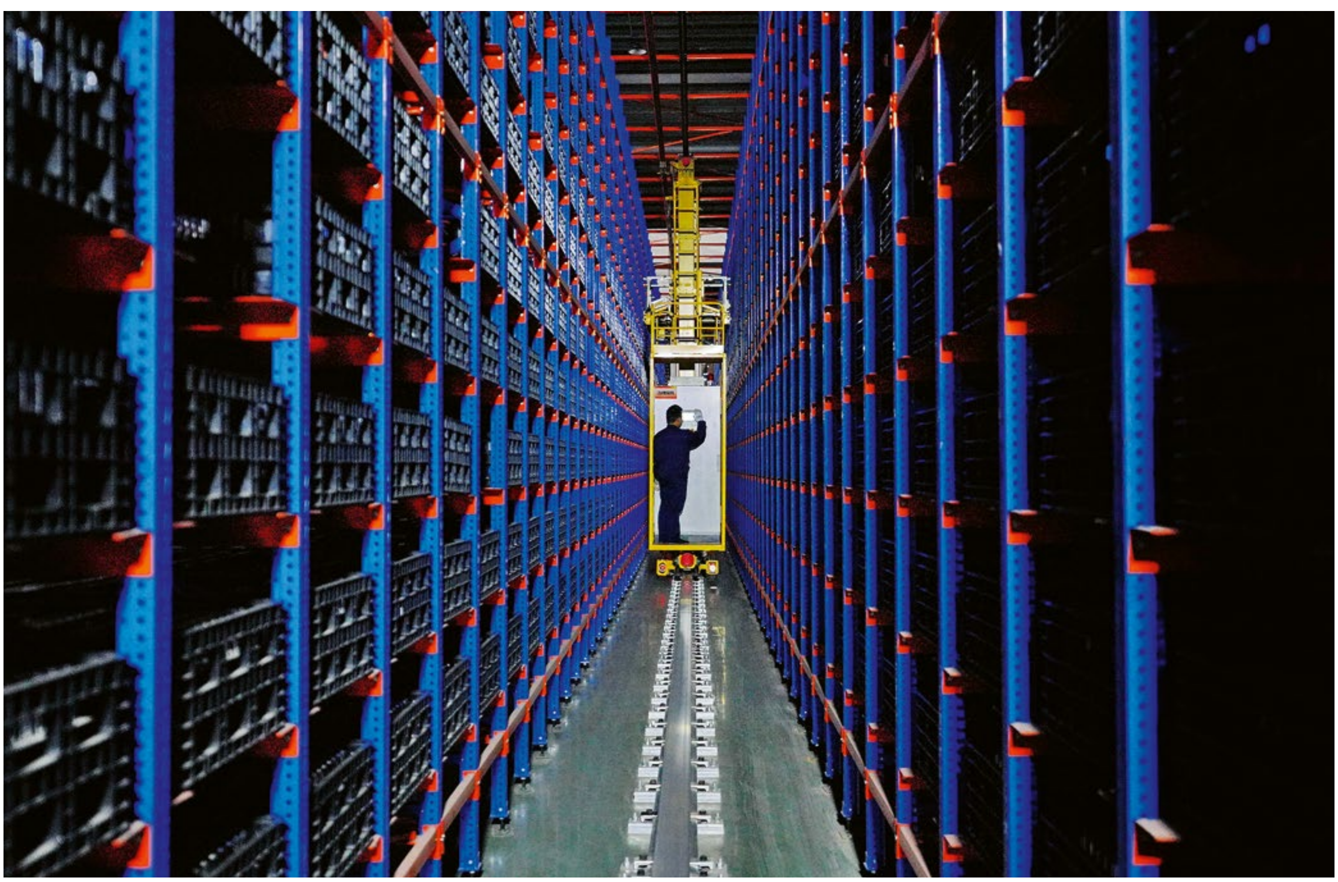
In the effort to extract even better performance from the currently available storage technologies, the lead-acid battery cannot be ignored. The traditional "automobile battery" is definitely not dead. In terms of the total storage capacity sold, it accounts for 70 percent of the world market. Lead-acid batteries with a total storage capacity of 400 gigawatt-hours are sold every year, and this figure is growing. Three quarters of these batteries are operating in automobiles with combustion engines.

Today these batteries as well are expected to perform better than they did in the past. Start-stop systems that switch off the engine when the car stops at a red light significantly increase the number of charging cycles and make demands on the battery in a wide range of states of charge. "The lead-acid battery really doesn't like these systems at all, but the most advanced versions of the battery cope with them well," says Dr. Jochen Settelein from the Fraunhofer R&D Center for Electromobility Bavaria (FZEB) in Würzburg. Settelein, an expert in the field of nanostructures, is the head of the Lead Acid Technology working group at the center.

This type of battery is too heavy, and its energy density is too low, for use in hybrid and electric cars. But that doesn't matter in other applications. For example, in a forklift a lead-acid battery actually provides the necessary tail weight that prevents the forklift from tipping forward during operation. In stationary power storage systems in particular, this supposedly age-old



In the 19th century, before a network of power plants and cables existed, buildings such as the City Hall of Paris were supplied with electricity by batteries



A storage depot for lithium-ion batteries: According to the International Energy Agency, 44 million new electric vehicles could be on the road as soon as 2030

Rechargeable batteries made of plastic

In the spring of 2019 Evonik presented a technology that makes it possible to print batteries made of plastic onto almost any surface. These batteries are wafer-thin, flexible, and environmentally friendly to boot. This technology, which is known as TAeTTOOz®, is based on redox polymers. These are plastics that can alter their electrochemical properties by using an oxidation process to emit electrons and also absorb them back again. The polymer batteries contain no metal or liquid electrolytes. For the logistics and packaging industry, they open up the possibility of sensors that can monitor delivery chains or the physical integrity of foods and medicines. Another interesting area of application for these flexible energy storage units is wearables—mobile devices that can be used to measure the wearer's bodily functions.

technology still has lots of future potential. The more that natural energy sources such as the sun and the wind are used, the more energy has to be retained in storage systems in order to balance out fluctuations in the power supply. According to the International Energy Agency (IEA), the worldwide installed power storage capacity almost doubled in 2018 alone. Most of this increase was due to electric batteries and "behind-the-meter storage"—in other words, consumers' individual power storage systems.

But major energy producers are also increasingly depending on electric batteries as temporary storage systems in order to smooth out network fluctuations and discrepancies between supply and demand. The IEA anticipates that the installed battery capacity for power grids will increase almost tenfold by 2040.

Lithium-ion batteries are in demand in this segment as well. For example, old batteries from electric cars can be reused here. And this is where the advantages of lead-acid batteries come to the fore. That's because their high weight and bulky dimensions play a very minor role in such applications, whereas their low price is all the more important. Lead-acid batteries cost only a third as much as lithium-ion rechargeable batteries per kilowatt-hour. What's more, they require no complicated charge control or cooling and they are environmentally friendly: About 99 percent of their component materials are recycled. The reusable-material cycle for lead has been well-established for decades, whereas for lithium it is still a distant goal.

ONE PROJECT, SIX PARTNERS

In order to exploit these advantages of lead-acid batteries for the benefit of the energy transition, Germany's Federal Ministry of Education and Research has been promoting the "AddESun" project at Settelein's Fraunhofer research center since 2017. The project's name mimics that of the electricity pioneer Thomas Edison →

> "With this configuration we are moving toward a physically determined performance plateau"
>
> CHRISTOS SARIGIANNIDIS, A CHEMICAL ENGINEER AT CREAVIS, ON THE LIMITS OF LITHIUM-ION BATTERY TECHNOLOGY

The applications engineer Herbert Habermann checks a separator that has been coated with aluminum oxide on both sides

Award-winning battery researchers

The excellent daily utility of the lithium-ion battery is due to three inventors who were honored with the Nobel Prize for Chemistry last year.

The British-American solid-state chemist **Stanley Whittingham** (below right) conducted experiments with tantalum sulfide and potassium for the multinational oil company Exxon in the 1970s. He discovered that layered sulfide takes up ions from a metal anode in its interstices. Experts call this process "intercalation." It generates an electric voltage between the anode and the cathode. Whittingham subsequently replaced the tantalum sulfide in the cathode with the lighter substance titanium and used the less volatile element lithium instead of potassium as the ion donor in the anode. Whittingham's first battery cell already generated two volts of electrical power, but it was highly explosive. After several charging cycles, the anode metal forms needle-like structures called dendrites. If they penetrate the cell and reach the cathode, they cause a short circuit. Back then, the local fire department had to rush to Whittingham's laboratory so often that it threatened to send him a bill for its services.

Not long after that, the American physicist **John Goodenough** (middle), who was working at the University of Oxford, took up Whittingham's idea. He suspected that oxides could take up more ions than sulfides do—and he was proven right. His cathode, which was made of lithium cobalt oxide, promptly generated four volts instead of two. In addition, Goodenough was the first scientist to realize that the batteries did not have to be manufactured in the charged state; they could also be charged after they had been assembled.

The last component of lithium-ion batteries, which was the key element of their safety, was contributed by the Japanese scientist **Akira Yoshino** (left). Unlike his forerunners, he was employed by a company that had its own electronics department, the Asahi Kasei Corporation in Japan. In the early 1980's, the company was placing great hopes in portable consumer electronics. Sony had just recently scored a global success with the first Walkman. Yoshino developed an anode made of cobalt that smoothly intercalated the lithium ions. If no metallic lithium is present, the danger of dendrites is eliminated. Thus Yoshino had discovered the structural design of the lithium-ion battery that is still valid today. Sony launched the first one on the market in 1991. B ERND KALTWASSER

and is a combination of the words "additive," "energy," and "sun." Evonik, which is one of the six project partners, is providing the additives—in particular, nanostructured oxide particles from Rheinfelden.

"With the additives from Evonik, such as aluminum oxide, we can increase the porosity of the electrodes," explains Settelein. The aim is to have the electrolyte penetrate more efficiently into the electrodes that have received the additives, just as a liquid soaks into the pores of a sponge. That way the electrolytes can reach the maximum area of reactive surface. This ambitious goal can be summed up in the formula "3×30": 30 percent more charging cycles should become possible, thus further extending the battery's service life. The battery's chargeability—its capacity for taking up electricity—should increase by 30 percent. And the battery's energy density—its storage capacity per kilogram of material—should also increase by 30 percent.

Settelein admits that when he started working at FZEB seven years ago, he himself was skeptical about just how much potential remained in the lead-acid battery. He adds that this makes it all the more fascinating to see what can still be coaxed out of it today.

THE NEXT GENERATION OF RECHARGEABLE BATTERIES

However, the researchers at Evonik are turning their attention to new technologies as well. That's because the theoretical limits of the established lithium-ion battery technology, for example, are becoming ever more clearly visible. "With this configuration we are moving toward a physically determined performance plateau," says Dr. Christos Sarigiannidis, a chemical engineer who is working on the next battery generation at Creavis, Evonik's central innovation unit in Marl. "We are investing great hope in solid-state batteries," he says. These rechargeable batteries function without liquid electrolytes—a property that should make them safer and more powerful. That would be reflected in increased ranges for electric cars, for example.

The first prototypes already existed in the late 1950s, but this technology has only been approaching market maturity for about the last five years. Many companies, ranging from the gigantic battery producer Panasonic to automakers such as Toyota, Nissan, BMW, and VW, are working to develop a practicable version of the solid-state battery.

True blue Lithium mining, shown here in the Uyuni salt flats in Bolivia, is a target of criticism by advocates of environmental protection and human rights. A five-person team led by Dr. Alessandro Dani at Evonik recently started working on a technology for recovering lithium from used batteries with the help of a selective ceramic membrane. The idea behind the project, which is called "Blue Lithium," was recognized with an in-house Evonik innovation award in 2019. Dani now has a six-digit budget to spend one year working exclusively on refining this idea

Even one of the inventors of the lithium-ion battery, John Goodenough, who is now 97 (see the box on the left), has joined the race. In 2017, his team from the University of Texas presented a solid-state battery that uses glass powder as the electrolyte. It is claimed to be at least twice as powerful as traditional lithium-ion batteries. What's more, it may be possible to replace the lithium it contains with sodium.

ENERGY FROM THE OCEAN

The sodium battery is a long-cherished dream of the battery industry. Lithium exists in large quantities on our planet, but it's not available everywhere. Today the largest producers are Australia and Chile. China has secured access to massive deposits of lithium. An even rarer substance is cobalt. Some 60 percent of the world's supply of cobalt is mined in the Democratic Republic of the Congo—often by means of slavery and child labor, practices condemned by advocates of human rights. By contrast, sodium is available all over the globe, at least in coastal countries. Every liter of seawater contains ten grams of this element on average.

Evonik is primarily interested in the solid-state battery. More than two dozen solid electrolytes are currently under consideration. They can be roughly categorized into three groups as inorganic materials, organic polymers or composites. "The crux of every solid-state battery is the balance between the electrolyte's ion conductivity and its mechanical properties," says Sarigiannidis. Each of the materials mentioned above has advantages and disadvantages. For example, as yet there is no polymer electrolyte with good conductivity at room temperature. Creavis is working together with various Evonik business units to evaluate a wide range of solid-state electrolyte technologies based on Evonik materials.

However, it will take quite some time before the next generation of batteries can be used in mobile phones or even in electric cars. "Solid-state batteries will probably not hit the market until about 2030," Sarigiannidis estimates. In view of today's continuously growing need for energy storage, the currently available technologies will continue to dominate for quite a while.

Full of Energy

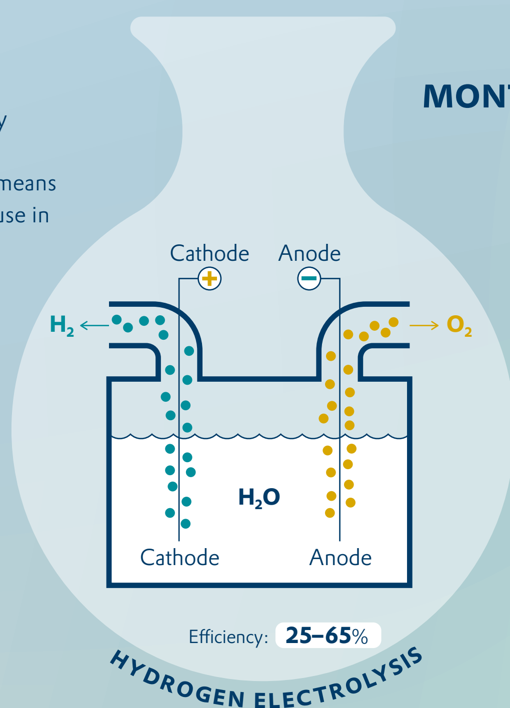
The energy transition can only succeed with the help of high-performance storage technologies. Various technologies are available for this purpose, depending on the area of application. But how do these technologies work, where are they used, and what are their advantages and disadvantages? An overview of the main techniques

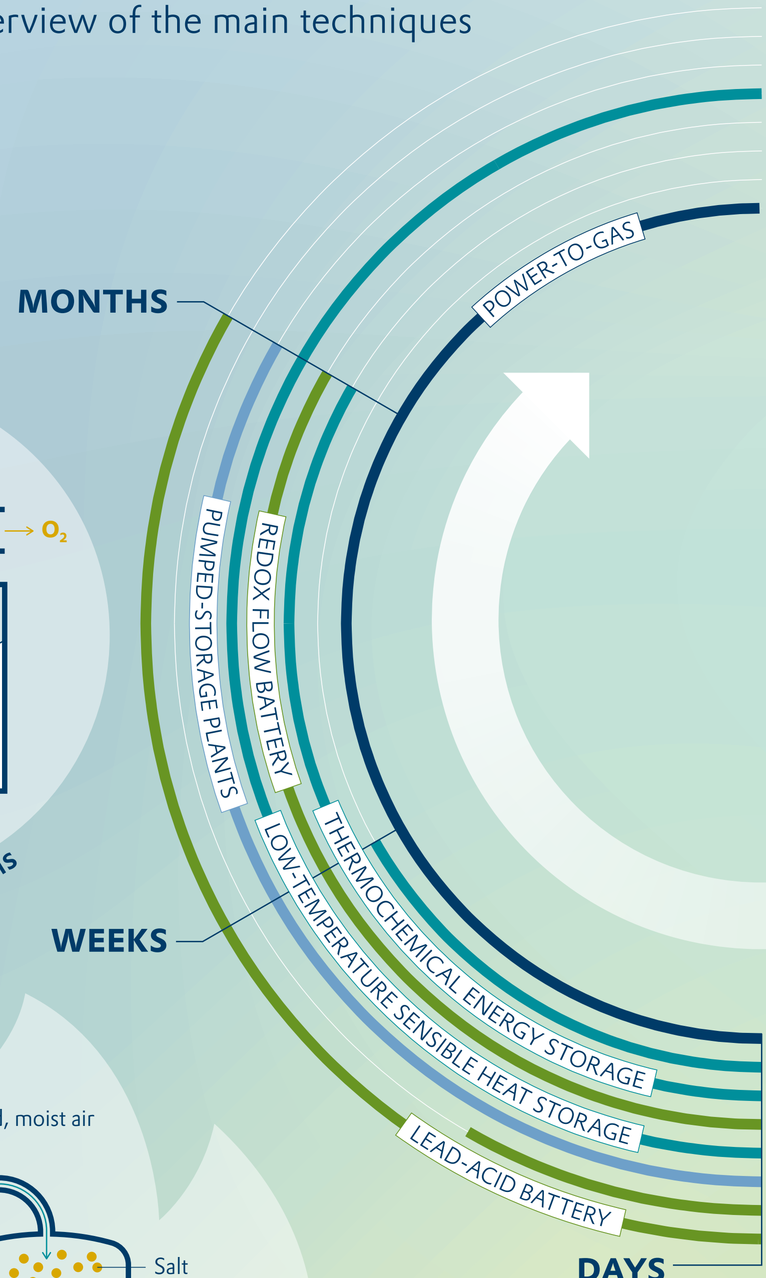
TEXT **LUCAS RIEMER**
ILLUSTRATION **MAXIMILIAN NERTINGER**

CHEMICAL STORAGE

Chemical energy storage converts low-energy substances into high-energy ones. Water, for example, can be converted into hydrogen by means of **electrolysis**. This principle is put to good use in the power-to-gas process, which uses surplus electricity to produce hydrogen.

APPLICATIONS Storage of surplus electricity from renewable sources
ADVANTAGES Storage possible for an unlimited time, easy to transport
DISADVANTAGES Because hydrogen can rarely be used directly, it has to be converted further (e.g. into synthetic gasoline), which decreases its efficiency

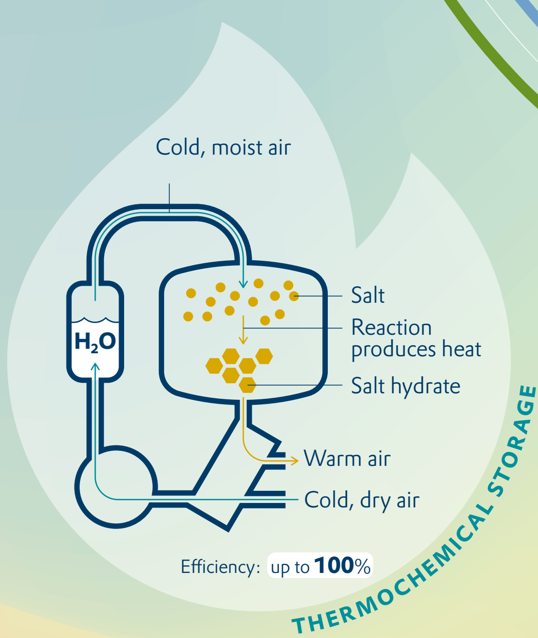


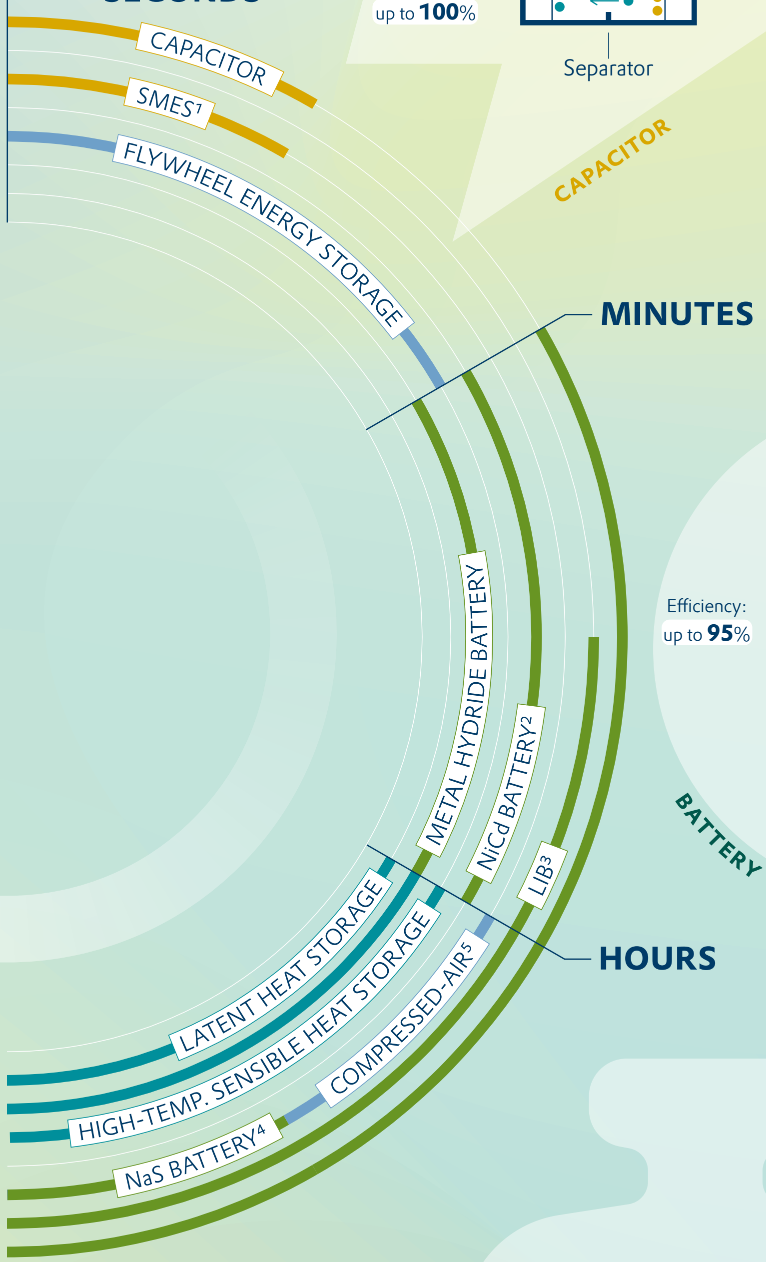


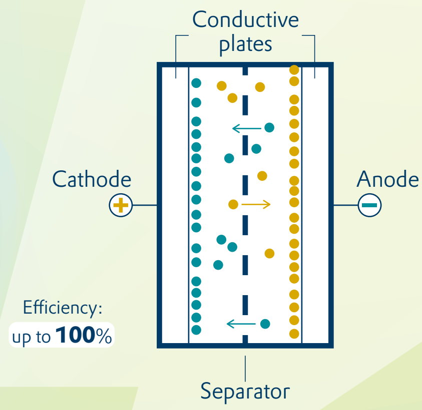
THERMAL STORAGE

Heat is mostly stored in liquids or solids. The possible storage times range from a few hours (storage heaters) to several months (heat batteries). The temperature of **sensible heat storage systems** changes as they charge and discharge. However, it remains constant in **latent heat storage systems**, although the storage medium undergoes a phase transition. **Thermochemical storage systems** store heat using endothermal and exothermal reactions.

APPLICATIONS Heating of process water and buildings, solar thermal power plants
ADVANTAGES Robust technology, low costs
DISADVANTAGES High energy losses in some cases due to waste heat



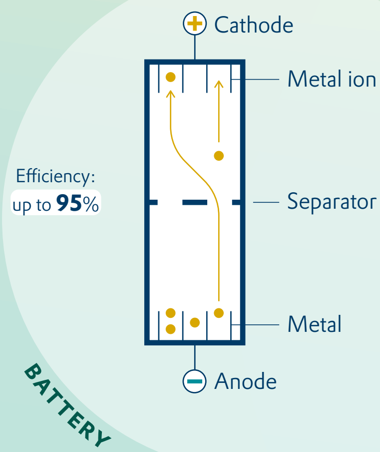




ELECTRICAL STORAGE

Capacitors store electricity with the help of an electric field. Today's **double-layer capacitors** are especially effective, due to their porous surfaces. Coils store energy in electromagnetic fields. **Superconducting magnetic energy storage** (SMES) operates according to the same principle.

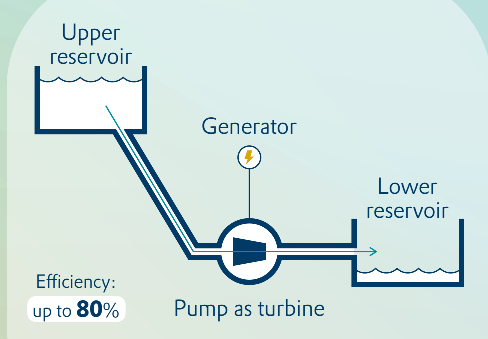
APPLICATIONS Short-term stabilization of power grids during peak loads; supplements batteries in hybrid and electric vehicles; bicycle stand lights (double-layer capacitors)
ADVANTAGES Very high efficiency, rechargeable many times, energy is quickly available
DISADVANTAGES High level of self-discharge, SMES needs to be cooled to below -200 degrees Celsius



ELECTROCHEMICAL STORAGE

The electrodes in normal and rechargeable batteries are connected by an electrolyte. During discharge, the chemical energy is converted into electrical energy. This reaction is reversible in rechargeable batteries. Whereas **lead-acid** and **lithium(Li)-ion batteries** work at moderate ambient temperatures, **sodium-sulfur batteries** only operate at temperatures above 200 degrees Celsius. **Redox flow batteries** use tanks to store energy.

APPLICATIONS Electric vehicles and small devices (primarily Li-ion batteries), offsetting grid fluctuations
ADVANTAGES High level of efficiency, fast response time, low self-discharge
DISADVANTAGES Fire hazard (Li-ion batteries), high cost and maintenance (redox flow battery)



PUMPED-STORAGE PLANT

MECHANICAL STORAGE

Electricity can be stored for long periods by converting it into other forms of energy. Examples include **compressed-air energy storage** and **flywheel energy storage**. **Pumped-storage plants** account for most of the electricity storage capacity worldwide.

APPLICATIONS Offsetting of peak loads in the power grid, safeguarding of the electricity supply, e.g. in hospitals (flywheel energy storage)
ADVANTAGES Relatively inexpensive, large amounts of energy can be stored for long periods (pumped storage), fast access (flywheel energy storage)
DISADVANTAGES Impact on landscape (except flywheel energy storage), high level of self-discharge (flywheel energy storage)

1 SMES
Superconducting magnetic energy storage

2 NiCd BATTERY
Nickel-cadmium battery

3 LIB
Lithium-ion battery

4 NaS BATTERY
Sodium-sulfur battery

5 COMPRESSED-AIR ENERGY STORAGE

Source: Energieagentur NRW, own research

SALT OF THE EARTH

Researchers in Eindhoven, Netherlands, are working on an ingenious thermal energy storage system for use in the energy transition. The main ingredient is also found in gingerbread

TEXT **TOM RADEMACHER** PHOTOGRAPHY **ROBERT EIKELPOTH**

"We store surplus heat in the cellar"

OLAF ADAN, HEAD OF HEAT-INSYDE

Olaf Adan has many jobs, but no desk. "It would be pointless for me to have one, because I travel around a lot," he says. Adan, a physicist, opens his laptop wherever his work takes him. Usually that's in the labs of Eindhoven University of Technology (TU/e) or in the TNO building on the other side of the city. TNO stands for Toegepast Natuurwetenschappelijk Onderzoek, the Netherlands Organisation for Applied Scientific Research. Eindhoven is home to one of the organization's research centers, where Adan heads the Materials Technology research area. At the TU/e, he is Professor of Applied Physics and heads the Transport in Permeable Media group. In this capacity, he uses retired MRT devices that he has adapted for his purposes in order to examine the interior of concrete parts, for instance. "It enables us to understand why fires cause tunnel ceilings to literally explode, for example."

However, Olaf Adan is currently especially busy as the Head of Heat-Insyde. This development consortium was founded last fall by eleven international project partners, including Evonik. The consortium receives almost €7 million in funding from the EU.

SOLAR ENERGY FOR COLD DAYS

Adan travels through half of Europe on behalf of Heat-Insyde. The countries he visits include Poland, Belgium, France, and Germany. He recently came to Lülsdorf near Cologne, where Evonik produces materials that play a major role in Adan's project. Adan and his team are working on a revolutionary technology that could help store thermal energy for buildings without any loss of energy and as long as desired. This could make the use of solar thermal energy more efficient and reliable. "Whenever the sun shines, we store surplus heat in cellars for use on cold, overcast days," says Adan. The system could store energy for more than just a few residential buildings, because entire communities and even large producers of district heating could use it to buffer peaks in supply and demand.

The Heat-Insyde project is located at the high-tech campus on the southwestern outskirts of Eindhoven. Over a period of two decades, around 200 startups, big companies, and research institutes have settled on this former Philips site, which is clustered around an artificial lake. Almost 40 percent of all the new patents registered in the Netherlands come from here. The researchers' first working heat battery stands in a small conference room on the third floor of the project building. The system uses a thermochemical material to store energy. It is based on the insights gained during two predecessor projects, in which TNO also took part.

One of these projects took place in Poland, where a few years ago a crane lifted a shipping container into the yard of a single-family home in order to provide it with sufficient storage capacity. The new demonstrator is much more compact than this. When put on rollers, it can be easily pushed through a room door. It mainly consists of just four components: a heat exchanger, a fan, an evaporator, and a reactor container. "The battery's simplicity is its biggest attraction," says Adan. The ground-breaking solution is contained in the reactor and consists of a layer of grains of a special salt through which the fan blows hot, dry air. The energy needed for this process can be supplied by roof-mounted solar thermal collectors, for example. Theoretically, any source of electricity could also be used for this purpose. The air heats up the salt, dries it, and releases water vapor into the airstream. The condenser extracts the moisture from the air until the salt is completely dehydrated. The battery is now charged. "The energy remains in the salt as long as I keep it dry," explains Adan. "All I have to do to get the energy back is to add moist air." →

The substance that Olaf Adan uses to coat his salt is a secret

Pim Donkers wrote his doctoral thesis about the thermochemical principle that forms the basis of the heat battery. He found out that potash (below right) is the perfect storage medium

In the heat battery, this role is also played by the fan, which now blows air that is cold and moist through the dry layer of salt. The salt absorbs the moisture from the airstream, heating the air up to over 60 degrees Celsius in the process. This heat can be used for space heating and for heating water. The underlying principle has been known to mankind for a long time: When crystals of certain salts absorb water, they release heat. Adan's co-worker Pim Donkers likes to demonstrate this effect to visitors by putting a glass full of small balls of such a salt into their hands.

He then squirts a good shot of water into the glass from a bottle. The water immediately disappears into the salt and the glass heats up. Five years ago, Donkers wrote his doctoral thesis about this surprising effect. To do so, he investigated almost all of the salts that could conceivably be used for this purpose. "Copper salts were my personal favorite," he says. "Unfortunately, they are much too expensive." Some of the other salts proved to be unstable or corrosive, or they even produced toxic gases. This made all of them unsuitable for a system that was meant to operate for decades in the cellar of a single-family home.

THE MAIN INGREDIENT: POTASH

Donkers eventually tested a salt that has a very high energy density and that can be very well hydrated and dehydrated at household temperatures. This salt is stable, harmless to use, and comparatively inexpensive. Its chemical name is potassium carbonate, and it is also known as potash. Potash is used in innumerable applications, ranging from cocoa processing to the production of crystal glass. In Germany, one of the best-known applications is in gingerbread production, where potash is used as the leavening agent. "This shows how harmless the material is," says Georg Dürr, who works at Evonik's Application Technology unit in Lülsdorf. The plant there has been manufacturing potash for the past 70 years. Evonik has an annual capacity of around 60,000 tons per year, making it one of the world's leading producers of potash. Potash is manufactured from potassium hydroxide, which Evonik produces itself using a very resource-conserving electrolysis technique. The base material is potassium chloride, which, like table salt, is mined in Europe and other parts of the world.

A BUILDING BLOCK OF THE ENERGY TRANSITION

Whereas baking enthusiasts can buy 15-gram sachets of potash in supermarkets, Evonik only sells the material by the truckload. That's why Dürr only found out about Heat-Insyde because he received an unusual inquiry from a distributor. "They wanted to have small product samples and asked us very unusual questions," recalls Dürr. After writing a few e-mails and making some calls, Dürr was on the phone with Olaf Adan himself. Shortly thereafter, Dürr drove the two-hour stretch to Eindhoven. A back-of-the-envelope calculation had made Dürr and his superiors sit up and take notice. According to the Bundesverband Solarwirtschaft (German Solar Association), there are almost 2.4 million solar thermal energy systems in Germany alone; 71,000 were installed in just one year. "Even if we can only reach one percent of that, it would still be a respectable market," says Dürr. "You have a product that is extremely versatile but also very well-known and seem-

The high-tech campus on the outskirts of Eindhoven is home to numerous tech companies, including Heat-Insyde

Olaf Adan (left) and his team are working together with Evonik. The Group's plant in Lülsdorf produces potash, for which Georg Dürr is trying to find new areas of application

ingly refined as far as it will go. But suddenly you don't just find a great market opportunity but also realize that it could possibly be a key component for the success of the energy transition."

PROTOTYPES IN SEVEN HOMES

However, much still needs to be done before this can be achieved. Although potash from Evonik has proven to be extremely suitable for this application due to its high purity, the demonstrator still has to be turned into a marketable product. This device should be no bigger than a washing machine but even simpler to operate. "You don't really need more than an on-off button," says Adan. The high energy density of potash, combined with the system's simple design, make the technology very appealing. "We expect that our heat battery will be only half the size of today's storage systems that use lithium-ion batteries, even though it will have the same output and cost only a tenth as much," says Adan. Although other common storage systems such as those that store heat in insulated water tanks are similarly inexpensive, they are about ten times bigger and also less effective. Moreover, the Heat-Insyde storage system would produce little noise and require little maintenance because it has only a single moving part: the small fan. Another bonus is that the salt can be completely recycled.

As is often the case, this ingeniously simple technology is the result of lots of scientific research. The salt is turned into a composite in order to keep it stable for decades and hundreds of charge-discharge cycles. The composite's composition is a carefully kept trade secret. In addition, the researchers are still working on an optimal structure for the salt layer and the particle size so that the airstream can flow through the reactor as effectively as possible. Another doctoral thesis being worked on in Adan's department focuses on doping—the intentional addition of impurities in the salt's crystal structure in order to improve its absorption rate and storage capacity.

The system's parameters are based on a typical range of requirements. "In our climate, you practically never have to store energy from solar thermal systems for more than 12 to 14 days," says Donkers. In order to demonstrate that the Heat-Insyde storage system can enable a four-person household to get by very well for two weeks in winter, near-series-production prototypes will be installed in seven homes in France, Poland, and the Netherlands by the summer of 2022 at the latest. "We have already been overwhelmed by applications," says Adan before departing with his laptop under his arm to his next appointment at the university.

Magic box IBM Q System One is the world's first circuit-based commercial quantum computer. The system is housed in an airtight glass cube

THE SIMULATION GAME

Quantum computers open up unimagined opportunities to researchers. For the first time, it might be possible to precisely simulate even complex molecules—and create completely new materials

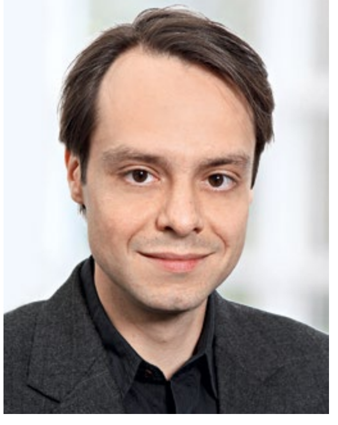
TEXT **BJÖRN THEIS**

Our ability to carry out even complex calculations in fractions of a second is thanks to two British mathematicians, a man and a woman. In the mid-19th century, Charles Babbage and Ada Lovelace laid the theoretical foundations for the modern computer through their concept of the Analytical Engine. Such a machine was not built during their lifetimes. However, a comparable computer was eventually constructed around 100 years later, in 1937, when Konrad Zuse presented the Z1—the world's first programmable binary computer. The power of our computers has been growing exponentially ever since. And science has profited greatly from this trend. Without computer support, most of today's cutting-edge research would not be possible.

But even supercomputers come up against their limits, which are a consequence of their binary operating principle. After all, our world isn't just made of ones and zeros. Max Planck taught us that we live in a quantum universe, in which energy cannot exist in arbitrary values but only in specific amounts. A computer that uses binary logic cannot run an exact quantum physical simulation of a molecule.

TRACKING DOWN MOLECULES

Richard Feynman was aware of this problem. At the Massachusetts Institute of Technology, he pointed out in 1981 that only a quantum computer would be capable of running such a simulation. Instead of bits—the classic units of information used by binary computers—a quantum computer would use qubits. Whereas a bit can only assume the values 0 or 1, a qubit can take either value—or a mixture of both. This principle is known as superposition. Superposed qubits can be "entangled" with one another and can in effect communicate with one another. This property enables quantum algorithms—the software of a quantum computer—to solve complex tasks by means of a kind of parallel processing.



Björn Theis heads the Corporate Foresight department at Evonik's innovation unit Creavis. His ELEMENTS column appears regularly at elements.evonik.de

For example, when simulating a molecule a quantum computer can analyze the entangled states of the electrons of the molecule by setting its own qubits in superposed and entangled states. This enables extremely large amounts of information to be processed simultaneously. A classic computer must, in contrast, carry out the necessary calculation steps sequentially, one after another. And that can take time. A modern supercomputer using the binary digital system would need more than ten billion years to carry out an exact simulation of the hormone insulin.

THREE MINUTES INSTEAD OF 10,000 YEARS

Feynman's thought experiment is starting to become reality. In 2016, the US tech company Google announced that it had used a quantum computer to exactly simulate a molecule of hydrogen. In 2017, the computer giant IBM simulated lithium hydride and beryllium hydride. In October 2019, Google announced that it had achieved "quantum supremacy." Google's computer, equipped with a chip on which 53 qubits work, had taken just over three minutes to carry out a calculation that a classic computer would need 10,000 years to solve.

Internet companies such as Alibaba, Google, IBM, Intel, Microsoft, and Rigetti are investing billions in the development of quantum computers, and so are national research centers, because these miraculous machines promise to achieve breakthroughs in the development of new catalysts, medications, and materials. According to researchers, it will take between five and ten more years of additional development before quantum computers can solve such practical tasks. The Corporate Foresight Team at Creavis has been continually observing progress in this field as part of the Digital Futures focus topic. That's how it can estimate how and when Evonik will be able to make use of this technology for its own purposes.

33 74,922 As Arsenic

"Arsenic solves the riddle of hidden gold"

Dr. Christof Kusebauch (36) is a scientist who works at the GFZ German Research Centre for Geosciences in Potsdam. As a geochemist, he investigates the structure of the earth's crust. One of his research areas is the gold deposits in minerals such as pyrite.

LOG **ANNA SCHRIEVER**
PHOTOGRAPHY **JONAS HOLTHAUS**

Arsenic is primarily known as a deadly poison, for example in the classic American film "Arsenic and Old Lace" and in Friedrich Schiller's drama "Kabale und Liebe" (Love and Politics). But in fact it has a healing effect in low concentrations, as do many active ingredients. It is still used today in medications. This element has been known since antiquity. It occurs naturally in the soil almost everywhere, in various concentrations. My colleagues and I have now identified it as the crucial element in the genesis of large deposits of gold.

In the Carlin gold deposit in Nevada, for example, this precious metal does not occur as nuggets or gold ore but instead is concealed, finely dispersed within pyrite crystals. Pyrite is an iron sulfide that is also known as fool's gold. Unfortunately, the gold that lies hidden in fool's gold can only be identified by means of chemical analysis. As a result, new gold deposits of this kind are not easy to find. For a long time it remained unclear how pyrites containing gold were generated and, more importantly, how they can be identified.

But now we have solved this riddle. For our study, we reproduced in our laboratory the conditions under which pyrite is formed. We streamed hot solutions containing sulfuric acid through carbonates rich in iron and thus produced pyrite crystals. To these hot solutions we added gold and arsenic in a range of different concentrations. We discovered that the higher the concentration of arsenic in the pyrite, the more gold can be deposited there. The arsenic acts more or less as a trailblazer for the gold. Its presence alters the pyrite in a way that enables gold to accumulate there more readily.

Three years of research work went into this study. The special challenge that faced us was reproducing the natural processes in the laboratory. The results of the study are highly relevant, because the demand for gold is still increasing, in the electronics industry for example. If we understand how gold deposits are formed, we can find them more easily. Now that we have shown that arsenic plays an important role in the accumulation of gold, it can serve us as an indicator of previously undiscovered gold deposits.

Masthead

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If you do what you've always done,

…you'll get what you've always gotten," according to the American icon Henry Ford. In the early 20th century, he followed his own advice and boldly entered uncharted terrain—with an innovative production method that revolutionized the industrial manufacture of cars: the assembly line.

Today, people like Henry Ford still exist—people who don't want to get what they've always gotten. These researchers and developers are forging ahead with the next phase of industrial production: 3D printing, which is the focus of the new issue of ELEMENTS. It's a technology that is fundamentally transforming the way we produce things—and opening up previously undreamed-of opportunities.

1/2020 **3D printing**

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